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USE OF ELECTRICITY IN THE CONTROL OF SEA LAMPREYS

SPECIAL SCIENTIFIC REPORT: FISHERIES No. 92

UNITED STATES DEPARTMENT OF THE INTERIOR
FISH AND WILDLIFE SERVICE

Explanatory Note

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Washington, D. C.
December, 1952

United States Department of the Interior, Oscar L. Chapman, Secretary
Fish and Wildlife Service, Albert M. Day, Director

USE OF ELECTRICITY IN THE CONTROL OF SEA LAMPREYS:

ELECTROMECHANICAL WEIRS AND TRAPS

AND ELECTRICAL BARRIERS

by

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Special Scientific Report: Fisheries No. 92

ABSTRACT

An account is given of experiments conducted in 1951 and 1952 with electromechanical and electrical barriers for the blocking and/or capture of sea lamprey runs in tributary streams of northern Lake Huron and northern Lake Michigan. Details are presented on structural characteristics, experimental manipulations, and effects on sea lampreys and other fish. All installations were operated from 110-volt alternating current power. On the basis of the experiments detailed, recommendations are offered on devices suitable for the control of sea lampreys under various stream conditions. The general structure and plan, and electrical characteristics of the devices must be adjusted to such factors as depth of water and extent of its fluctuation, rate of stream flow, physical nature and conductivity of bottom materials, conductivity of water, and need for the protection of fish that migrate simultaneously with the sea lamprey.

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USE OF ELECTRICITY IN THE CONTROL OF SEA LAMPREYS:

ELECTROMECHANICAL WEIRS AND TRAPS

AND ELECTRICAL BARRIERS

Five types of mechanical control devices have been developed for reducing the numbers of sea lampreys in the upper Great Lakes: (1) large, permanent-type weirs and traps; (2) and (3) portable-type weirs and traps for medium- and small-size streams; (4) barrier dams; and, (5) dams and inclined-screen traps. Structures (1) through (4) accomplish the destruction of spawning runs or block them from reaching spawning grounds; the inclined-screen traps destroy young, recently transformed sea lampreys on their way downstream to the "big" lakes (Applegate, 1950, 1951; Applegate and Smith, 1951a, 1951b; Applegate and Brynildson, 1952; Applegate, Smith, McLain and Patterson, 1952).

Of these structures, the more or less conventional weirs and traps are adapted to the widest usage in Great Lakes streams. Although these devices have proven to be effective and positive instruments for controlling the numbers of sea lampreys, their operation is expensive and fraught with frequent danger of breakdown under flood conditions with resultant escapement of mature adults to the spawning grounds.

In an effort to circumvent these difficulties, preliminary tests were performed in 1951 to determine if the usual screens or grates of the sea lamprey weir could be supplanted by a simple, alternating current, electrical field which would control all lamprey and fish movement in the stream while permitting unhindered downstream passage of flood waters and debris. The results of these preliminary tests were highly encouraging. They demonstrated that an effective and practical electromechanical sea lamprey weir and trap could be built and operated with greater efficiency and at appreciably less cost than the strictly mechanical type control devices.

In order to develop and improve the structural characteristics of the electromechanical device (electrode pattern, method of electrode mounting, ...) four pilot models of diverse design were installed in streams and tested during the spring of 1952. Descriptions of experimental equipment, test procedures, and summaries of results in each year with recommendations for application of several devices in Great Lakes tributaries are presented.

Installation of first experimental electromechanical weir and trap in 1951

During the period May 2 - May 9, 1951, an experimental electromechanical weir was assembled and put into operation in the Ocqueoc River, Presque Isle County, Michigan, immediately downstream from the mechanical weir and traps in that river (Figs. 1 and 2). A 25 KVA generator was set up in a cabin on the west bank of the Ocqueoc River adjacent to the mechanical weir. Power transmission lines were strung from the generator to a wire lead distribution platform positioned a few feet above the midpoint of the weir. Manipulation of individual leads to each electrode could be accomplished at this platform.

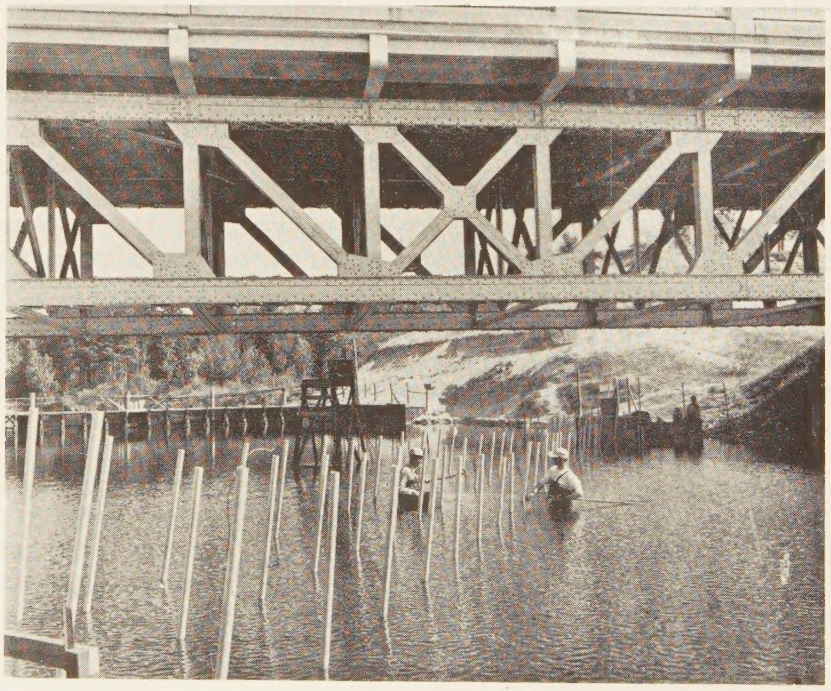

Figure 1. Experimental electromechanical weir and trap installed in the Ocqueoc River in 1951.

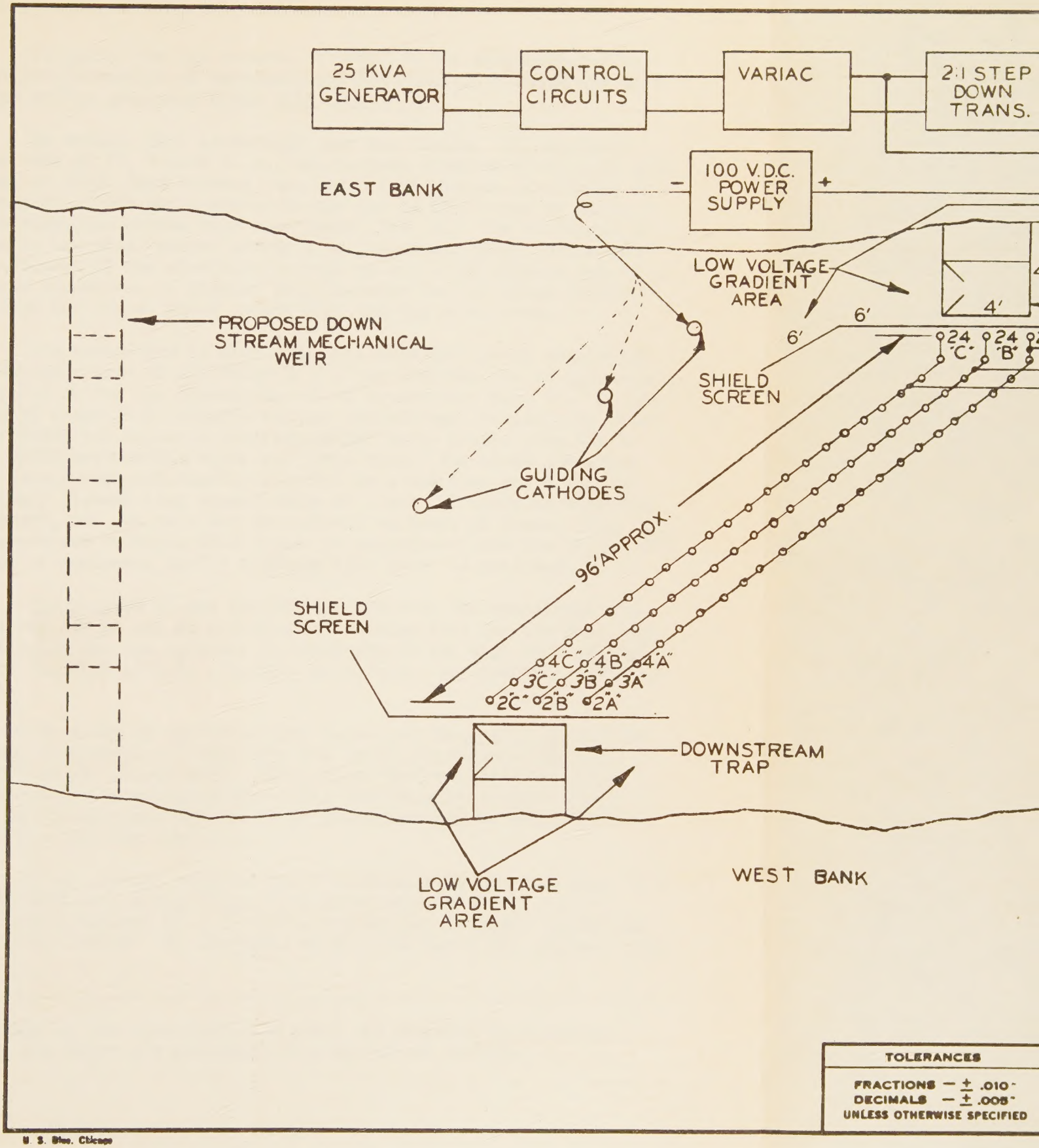

Fig. 2--Plan and block diagram of experimental electromechanical weir and trap Ocqueoc River in 1951.

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Circuitry for the control of power to the electromechanical weir and for protection of personnel against electrical shock was also installed in the generator cabin (Fig. 3).

In detail, this electrical weir was simple. It consisted of three rows of 23, 2-inch O. D., non-buoyant aluminum electrodes with a spacing of 3-1/2 feet between rows and 4 feet between electrodes in a row. Each electrode was anchored to the bed of the stream by means of a 4-foot steel pin driven into the bottom (Fig. 4). The electrode was attached to the steel anchor pin by a spring-loaded hinge, which permitted movement of the electrode through an arc of 60 degrees only in a downstream direction. A plastic plug isolated the electrode (electrically) from the hinge, steel anchor pin, and the stream bed.

The center row of electrodes was made the common connection for a voltage source of 110 volts AC for the upstream row of electrodes, and 55 volts AC for the downstream row of electrodes (Fig. 2). It was possible by means of a variable voltage transformer (variac), to raise or lower these two voltages simultaneously, while maintaining the 2 : 1 voltage ratio between the upper and lower rows. The above indicated voltage levels were arbitrarily selected as a starting point for the tests simply because they seemed ample to block the upstream migrating sea lampreys, and yet were not excessively wasteful of power. They further represented voltages which could be introduced into the stream with a minimum of equipment should ordinary line power be utilized.

The purpose of the low voltage field on the downstream side of the array was to act as a non-lethal warning area for the game fish while allowing the sea lampreys to penetrate to the high voltage field, which was expected to have a lethal, paralyzing, or diverting effect on them. 1/

The array of electrodes was installed diagonally across the stream and a conventional weir-trap was installed between each end of the array and the stream bank. These traps were bordered on their streamward sides by wooden baffle walls covered with a metal screen which acted as an electrical shunt in preventing the extension of the fringe field into the trap area.

After initial tests of the electrical weir had indicated that some game fish were being turned back downstream, a direct current guiding field, powered by a 100 volt, continuous, DC power supply was installed and tested. It consisted of an anode above the upstream trap

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1/ Comments on the reactions of migrant sea lampreys to electrical fields in the water are presented in a subsequent section.

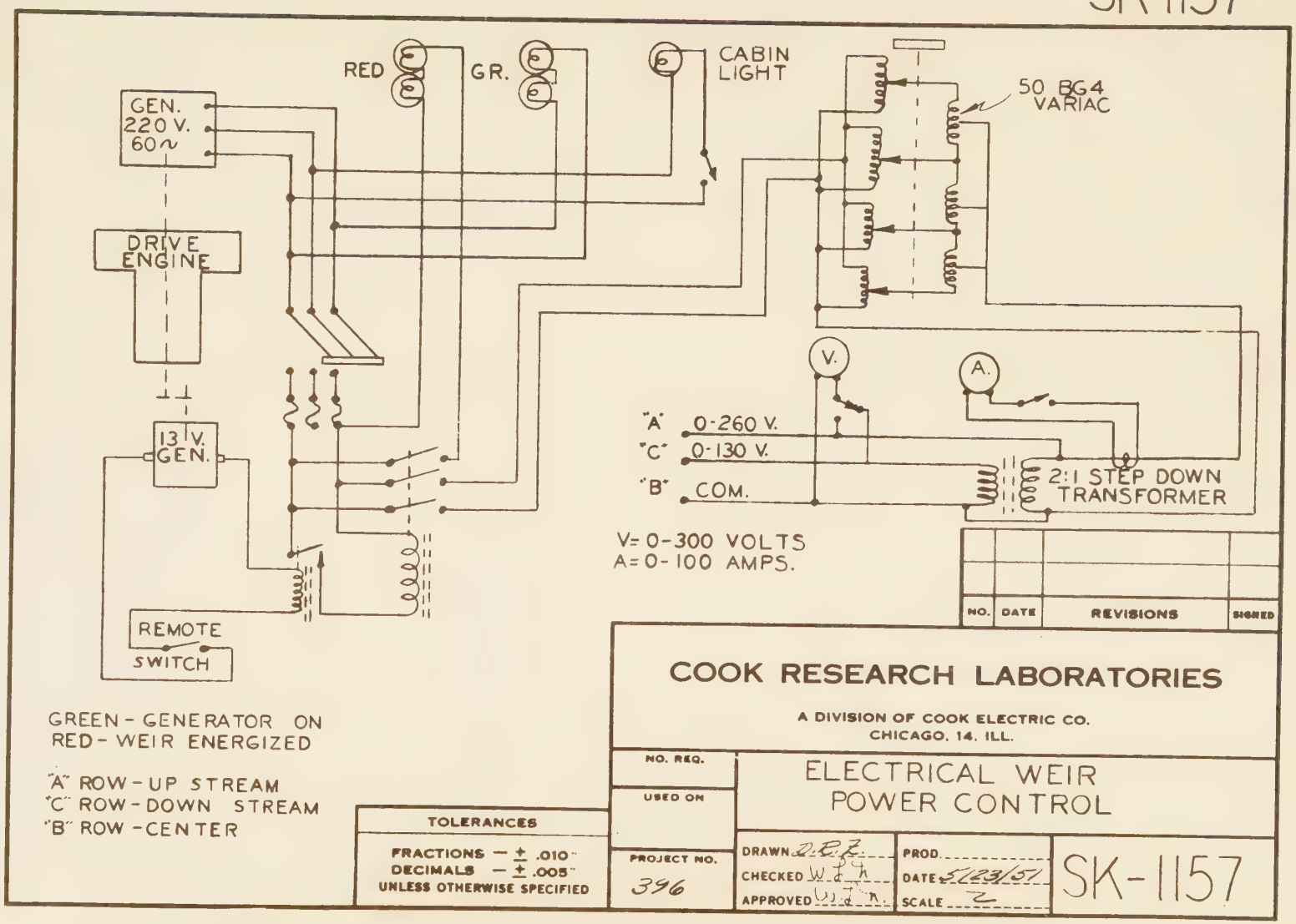


Fig. 3--Electrical circuit diagram of experimental electromechanical weir and trap installed in the Ocquec River in 1951.

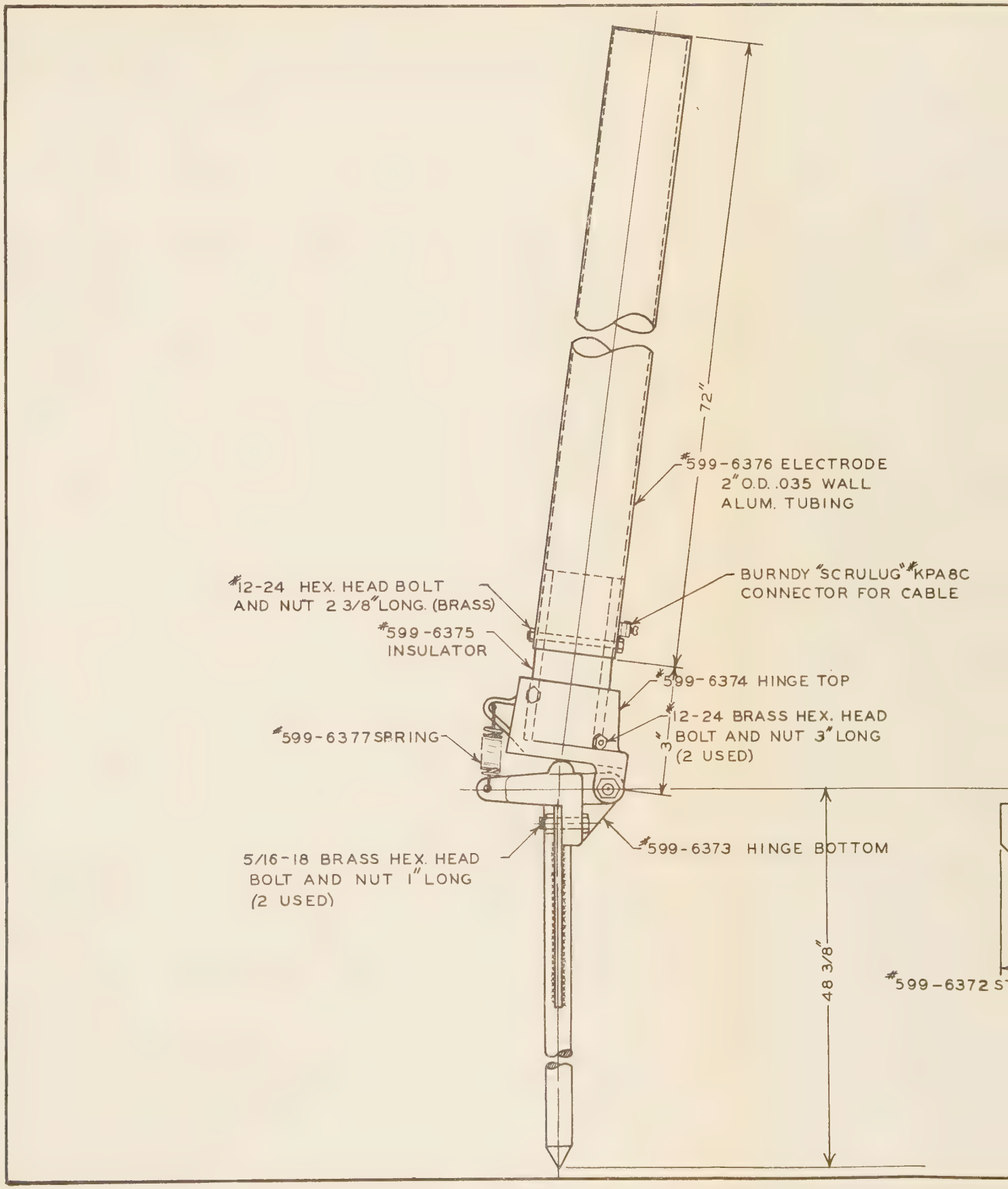


Fig. 4 Drawing of ground-mounted electrode and stake as

and a cathode placed in various positions downstream from the electromechanical weir. Three different cathode locations were tried in a series of tests of this system.

Operation and testing procedures

The electromechanical weir and trap was operated almost continuously from May 9 until June 8 with interruptions only for changes in circuitry and electrode configuration. It was originally intended that the permanent Ocqueoc River sea lamprey weir and trap, located about 200 feet upstream from the electrical device, should serve as a checking structure of the effectiveness of the electromechanical weir. To a certain extent the permanent weir and trap served this checking function and catches in both devices were compared regularly throughout the test period. However, small escapements of migrants through the electrical device occurred during periods in which the power was shut down for the purposes of making certain checks and measurements. The permanent weir and trap, therefore, could not serve as a true measure of the efficiency of the electrical device. All conclusions concerning this device are based primarily on direct, visual observation of the very large sea lamprey run entering the river during the period of the tests. Fairly clear water, low river levels and good observational facilities left no doubt in the investigators' minds as to the effectiveness of the device under any of the applied conditions.

At least two men were present during every hour of operation, observing the individual behavior of lampreys and fishes approaching and/or entering the electrical field. Observations at night were aided by several spot-lights. 2/ Service crews emptied the traps of both the electromechanical device and the checking weir regularly and turned over catch records to the observers on duty as supplemental evidence concerning the device's efficiency at any given time.

In the initial tests a 2 : 1 voltage ratio was maintained between the upstream and downstream rows of electrodes. Numerous voltage levels ranging from 150/75 down to 50/25 were employed. Power consumption at these limits was approximately 9 KW and 1 KW, respectively, varying slightly with water level. Further tests were conducted maintaining a voltage ratio of 1 : 1 between the upstream and downstream rows of electrodes. Voltage levels were employed ranging from 110/110 down to 50/50. In these tests, power consumption ranged from 7.5 KW to 1.4 KW.

2/ It is a point of some biological interest that in none of our observations did we find that illumination of any intensity, within the range which we employed, had any effect on the normal migratory behavior of the sea lampreys.

Voltage gradients created in the water during each test conducted were measured, recorded, and correlated with effects on fish and lampreys. A specially designed probe and a vacuum tube voltmeter were used to obtain these measurements. A more detailed description of test instruments is included in a later section.

Summary of results in 1951

(1) The experimental electromechanical weir and trap, utilizing as little as 2 KW of power, effectively killed, trapped, or diverted all sea lampreys entering the river. The results obtained at this low power level are amazing in view of the fact that it was necessary in this river to energize 1,400 cubic feet of water and that an appreciable percentage of the power input was dissipated in the stream bed. By way of comparison, it might be pointed out that this power consumption is roughly four times that required by a domestic electric iron.

(2) Specifically, satisfactory results were achieved utilizing the 2 : 1 voltage ratio between the upstream and downstream rows of electrodes with voltage levels as low as 70/35 (2 KW power consumption). Similar results were obtained with the 1 : 1 voltage ratio between rows with voltage levels as low as 70/70 (2.7 KW power consumption). At lower voltage levels in both applications (60/30 and 60/60 and lower combinations) some escapement of lampreys occurred. Consideration of all factors indicated, however, that in general practice somewhat higher voltage levels than the minima found effective should be used in order to provide some margin of safety. Input voltages in the order of 110 provided an adequate margin of safety and at the same time had the distinct advantage of being easily obtained from conventional power sources (power line or generators).

(3) It was determined that a minimum voltage gradient of 0.75 volt per inch must exist in the water between electrodes at least in the upstream half of the array (center row to upstream row of electrodes) if the electrical field is to block the lampreys effectively. Where weaker gradients exist between electrodes in the upstream half of the array, some escapement of lampreys through the field occurs. If an adequate margin of safety is desired, the minimal voltage gradient between electrodes of the common and upstream rows must be at least 1.0 volt per inch.

(4) It was tentatively considered desirable to maintain the effect of a so-called "incremental field" created by the application of voltage levels in a 2 : 1 ratio between the upstream and downstream rows of electrodes. The weaker electrical field on the downstream side of the array seemed to repel migrant food and game fishes before they could be harmed by abrupt contact with the higher voltages required in

the upstream half of the array. A further desirable effect of this application is realized in that more sea lampreys are retained in a paralyzed state in the electrical field until killed by suffocation.

(5) The ground-mounted, non-buoyant electrodes were not satisfactory at least in the stage of development achieved during tests in 1951. Although the initial cost of a ground-mounted electrode array was calculated to be less than that for a system of suspended electrodes, this advantage was outweighed by numerous disadvantages both electrical and mechanical. Siltation around the electrode mountings caused appreciable losses of power into the stream bed. Further losses of power resulted from the close proximity of the electrodes to a good electrical ground in the form of the steel anchor pins. Susceptibility to damage or displacement by heavy floating debris was great. Wire leads to electrodes, lying on the bed of the stream, were easily damaged and difficult to repair. From the mechanical standpoint, the spring-loaded hinge was not a satisfactory electrode mounting. No practical method could be found to prevent debris from collecting inside the hinge and jamming it open.

Ground-mounted, buoyant electrodes likewise were found to be unsatisfactory. In addition to exhibiting most of the drawbacks indicated above, the buoyant type produced distorted electrical fields and drew unnecessary amounts of power during low-water stages when the electrodes were lying almost flat on the water.

(6) It was observed that spawning runs of certain food and game species, migrating simultaneously with the lampreys, were wholly or partially blocked by the AC field. These species did not "lead" well along the margin of the electrical field and enter the upstream traps (from which they could then be transferred upstream). Some of the species which were thus blocked, such as the suckers, can spawn in the lake proper; consequently their exclusion from stream spawning grounds is not a serious consideration. However, in the interests of protecting the runs of several species which are not so adaptable in their habits, experiments were performed with a DC guiding field located on the downstream side of the electrical weir. No positive evidence of the effectiveness of this accessory device was obtained. Its failure to guide fish into the upstream trap may have been due to one or both of the following reasons: (a) The shield screen, which was necessary to isolate the trap electrically from the strong AC fields at the upstream end of the weir, so completely dispersed the DC guiding field at the attracting electrode (anode) (as evidenced by voltage gradient measurements in this area) that the fish were not able to sense the positive direction; (b) DC voltage gradients were insufficient as a result of power limitations of the device (100 volts DC at one ampere).

Extensive tests subsequently undertaken in the laboratory for the further development of this accessory guiding mechanism resulted in some success in guiding or "leading" certain species of fishes to a desired point in a body of water. Unfortunately, other limitations of this "leading" device which tended to reduce its utility presented themselves during the experiments. Details of these experiments will be presented in a separate report. 3/ Subsequent experiments in 1952 demonstrated other methods of holding mortality of migrating fishes to a minimum (See "Summary of results in 1952").

3/ McLain, Alberton L. and Willis L. Nielsen. Directing the movements of fish with electricity. (Scheduled for publication as a Special Scientific Report, U. S. Department of the Interior, Fish and Wildlife Service).

Installation of electrical sea lamprey barriers in 1952

In general, a practical, economical electrical device for blocking and/or capturing migrant sea lampreys was evolved from the experimental electromechanical weir operated in the Ocqueoc River in 1951. Using 2-inch diameter tubes as electrodes arranged on 4-foot centers in a diamond pattern it was determined that migrant sea lampreys could be blocked and/or diverted (or destroyed within the array) if a minimum voltage gradient of 0.75 volt, AC per inch was established on a line between the center and upstream rows of electrodes. Such a minimum gradient between the above named rows of electrodes was conveniently obtained at a 110 volt input to the array. The device functioned effectively on very small amounts of power at common line power voltages or simple reductions of these voltages.

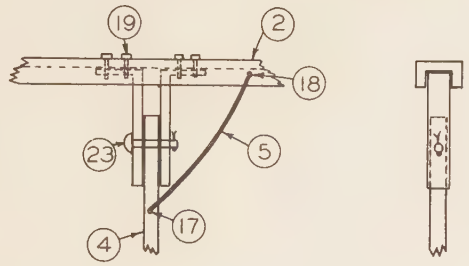
In view of the low power requirements of the device, elaborate experimentation directed particularly at further reducing said power requirements was not undertaken during the 1952 season. However, experiments directed at reducing the amount of physical equipment required in a given device could and did result in reductions in power demand. It was further deemed of no immediate practical advantage to engage in experimentation that would lead to the use of some odd input voltage level requiring special or additional transformers, etc. (e. g., indiscriminate and arbitrary changing of electrode spacing and array pattern, particularly in the upper half of incremental fields, for purposes other than to compensate for varying electrode diameter and efficiency). Reductions in numbers and rows of electrodes and changes in electrode systems were accomplished where swift water velocities occurred at test sites but experimentation was not carried beyond the point where input voltages greater than 110 would be required to block or divert the migrant lampreys.

The four pilot model alternating current devices installed in 1952 were designed primarily: To demonstrate the practicality and economy of this type of sea lamprey control device; to provide suitable facilities for improving the mechanical design of the devices; and, to permit investigations of various power supply problems. Because the experiments of the preceding year had brought out rather clearly many of the major electrical characteristics of an effective barrier, it was considered necessary to provide only limited flexibility in the 1952 installations for experimentation of an electrical nature. These structures were designed primarily with a view toward mechanical flexibility adequate for the solution of certain problems of construction and installation that had been raised by the previous years experience. Further information on mechanical problems was obtained by variation from device to device in the structural components.

The devices were located in the following streams: (1) Kewaunee River, Kewaunee County, Wisconsin; (2) Squaw Creek, Delta County, Michigan; (3) Hibbards' Creek, Door County, Wisconsin; and, (4) Carp Creek, Presque Isle County, Michigan. A summary of the equipment and characteristics of these installations follows:

(1) Kewaunee River electromechanical weir and trap.--This installation consisted of an array of three rows of electrodes suspended by a system of overhead cables which in turn were supported by a pair of steel poles at each bank (Figs. 5 and 6). Each row was comprised of 23 or 24 electrodes of 1-1/2 inch standard galvanized pipe, spaced on 48-inch centers, which were hinged to, and suspended from, a 3-inch channel iron rail. Spacings between electrodes could be increased in increments of 2 feet for experimental purposes. Electrode lengths varied from 2-1/2 to 5 feet since they were cut to fit the contour of the stream bed. The center row of electrodes was offset 24 inches to give a "diamond" or "X" pattern to the electrodes in the total array.

Figure 5. Electromechanical weir and trap installed in the Kewaunee River in 1952.



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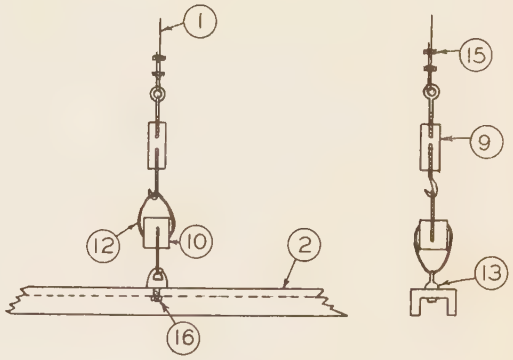

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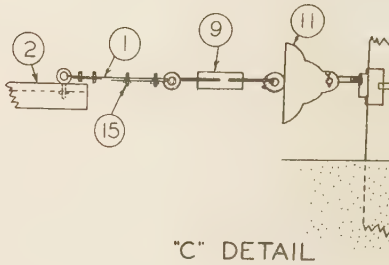

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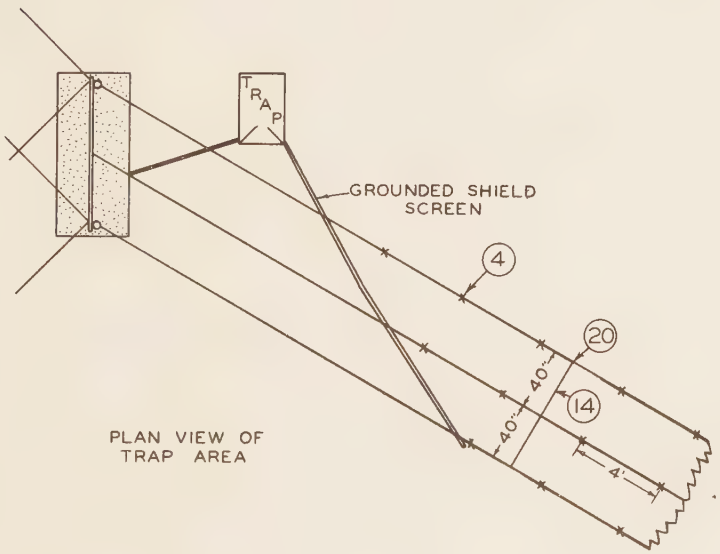
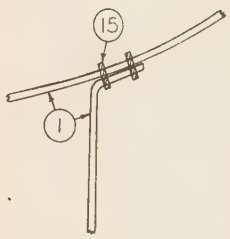


PLAN VIEW OF TRAP AREA



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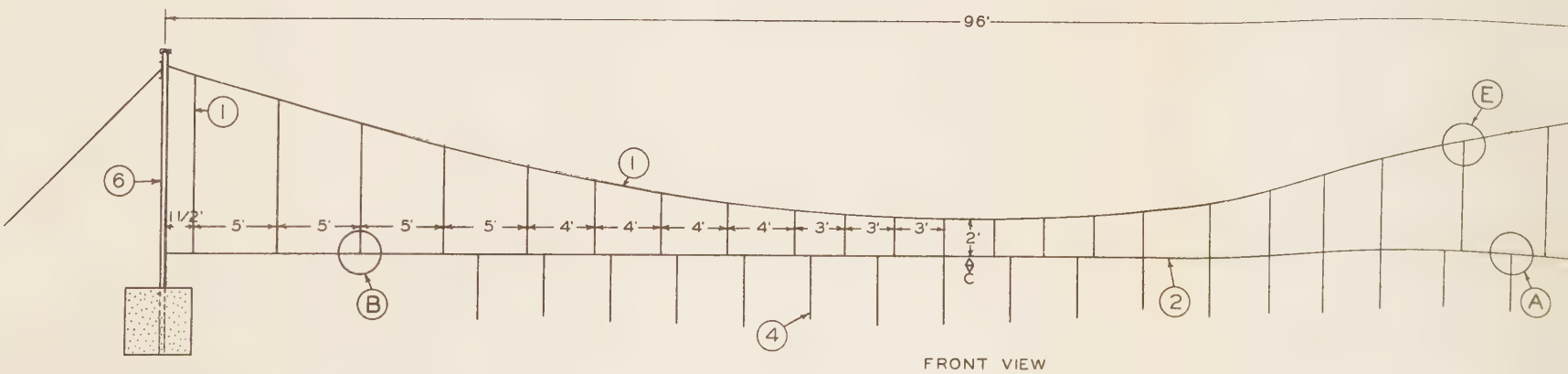


FRONT VIEW

Fig. 6--Drawing of electromechanical weir and trap installed in the Kewaunee River in 1952.

At the point of installation, the stream was 66 feet wide; its average depth varied from 9-1/4 to 21-1/4 inches during the period of experimentation with the device. The array of electrodes, which was 96 feet in overall length was mounted diagonally across the stream; a conventional weir-trap was installed between the upstream end of the array and the stream bank (See Applegate and Smith, 1951, for "portable weir" trap design). The trap was shielded on its streamward side by an electrically "grounded" metal screen.

The electrodes in each row were connected in parallel in order that the three rows might be energized in various combinations (Fig. 7). The "B" (center) row of electrodes in all cases was made the common connection for a voltage of 110 VAC to the "A" (upstream) row and a voltage of 55 VAC or 110 VAC to the "C" (downstream) row. Thus, operation as a uniform field barrier or as an incremental field barrier was possible. In addition, the voltage gradient within either field could be controlled to some extent by changes in the spacing of electrodes in the individual rows.

In certain of the experiments involving incremental fields, a non-lethal "warning" field between the "B" and "C" rows of electrodes was achieved by the application of 55 VAC, or one-half the AC line voltage, across these two rows of electrodes. A 60 cycle, 2 : 1 stepdown autotransformer was used for this purpose. In other similar experiments, the effect of reduced voltage gradients in the downstream half of the field was produced by increasing the spacing of "C" row electrodes to 8-foot centers and connecting this row to the same source of voltage as the "A" or upstream row.

The Kewaunee River electromechanical weir was tested both as a two-row and as a three-row system over a wide range of field intensities by the use of various combinations of electrode spacings and voltages. Following is a tabulation of the combinations tested:

Test number	Electrode spacing in row			Voltages	
	"A"	"B"	"C"	"A" to "B"	"B" to "C"
1	4'	4'	4'	110	55
2	6'	6'	6'	110	55
3	8'	8'	8'	110	55
4	4'	4'	8'	110	110
5	-	4'	4'	0	110

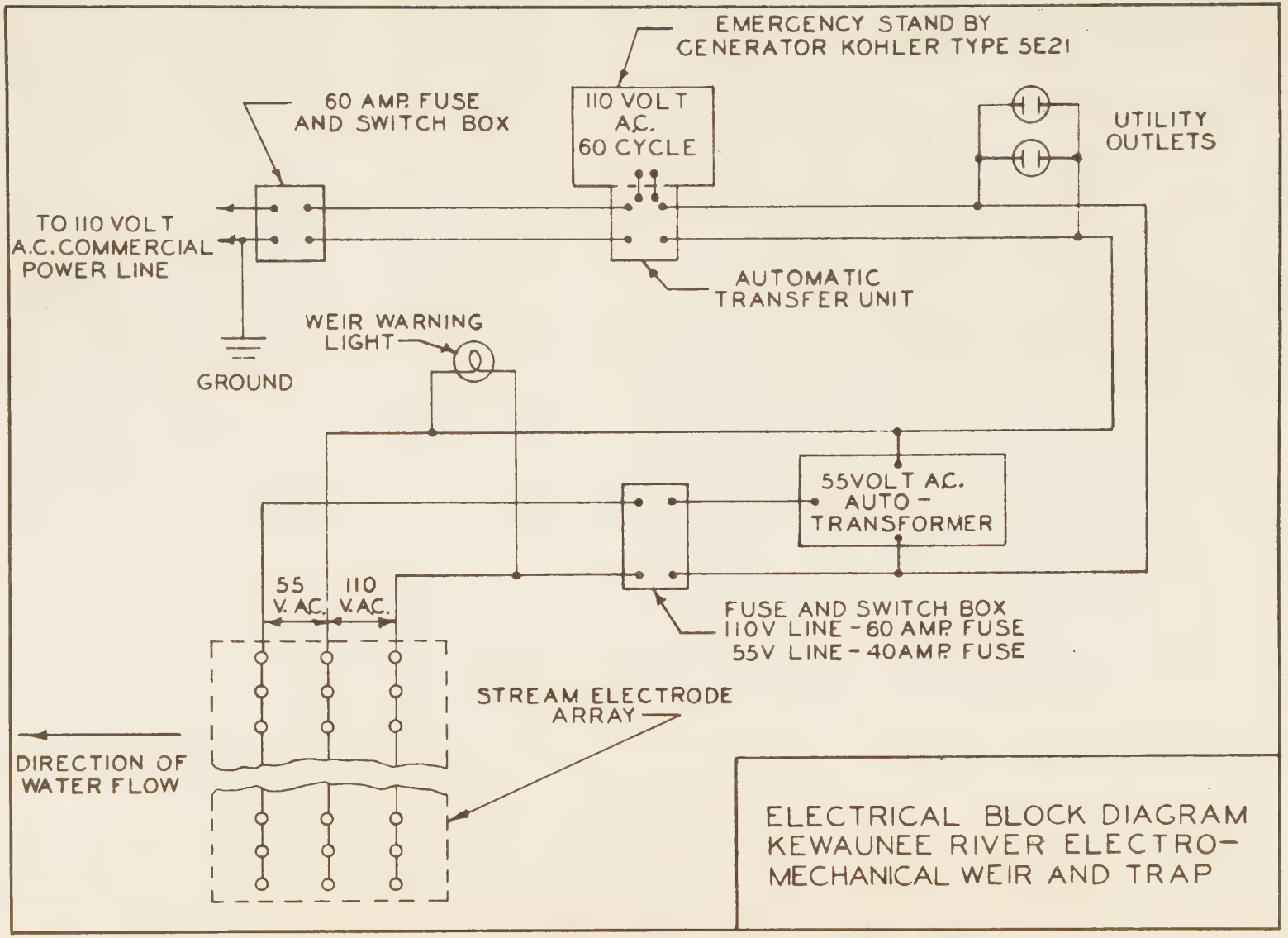


Fig. 7--Electrical block diagram of electromechanical weir and trap installed in the Kewaunee River.

The normal source of power for the Kewaunee River device was a 60 cycle commercial power line. A distribution transformer supplied 110 VAC to fuse and switch boxes, the autotransformer, and the gasoline engine-driven, 5,000 watt, AC generator, which served as the emergency source of power. All of this equipment was housed in a small building. The generator unit was equipped with automatic starting controls and connected to both the normal source of line power, and the electromechanical weir in a manner such that immediately upon failure of line power the generator started automatically and provided an uninterrupted flow of power to the weir. The generator unit was also equipped with a battery charging circuit which automatically maintained the starting batteries at full charge at all times.

The generator building also contained electrical outlets for the continous operation of red warning lights mounted over the electromechanical weir, and for the operation of floodlights as an aid to visual observation of the sea lamprey runs during the hours of darkness.

(2) Squaw Creek electromechanical weir and trap.--The Squaw Creek electromechanical weir was of essentially the same design as the Kewaunee River installation (Fig. 8). It differed from the latter in only the following respects: Each of the three rows of the array consisted of 11 or 12 electrodes, 5 feet long, which were made of 3/4-inch O. D., thin-walled conduit; the electrodes were hung on 3-foot centers and the interval between adjacent rows was 3 feet. The above indicated reductions in spacing were effected in order to maintain voltage gradients in the array at the same level as those resulting from the use of 1-1/2 inch diameter electrodes spaced on 4-foot centers.

Squaw Creek was 41 feet wide at the point of installation and average water depth varied from 6 to 18 inches during the period of operation. Unlike the Kewaunee device, the Squaw Creek array was installed directly across the stream at a 90-degree angle to the direction of water flow. An electrically shielded trap was located at midstream, directly under the supporting rails. Electrodes in the center of the array were removed to accommodate the trap.

Electrical circuitry was identical with that of the Kewaunee River device; three connections were made to the array, one for each row of electrodes. In all experiments conducted at the Squaw Creek site, the electrode spacing was fixed at 3 feet. With 110 VAC applied to the "A" (upstream) row, the array was tested with 55 VAC or 110 VAC applied to the "C" (downstream) row ("B" row serving as common connection).

Two 3,500 watt gasoline engine driven generators housed in a small building, together with fuse and switch boxes and a 2 : 1 stepdown autotransformer, provided an uninterrupted supply of power to the weir. One of the generator units operated as the normal source of power, while the second unit served as an automatic emergency source of power ("standby"

Figure 8. Electromechanical weir and trap installed in Squaw Creek in 1952.

generator). The generators also had adequate reserve power for the operation of utility lights, warning lights, and such floodlights as were used for night time observations.

(3) Hibbards' Creek electrical barrier.--This device was composed of two diverse elements: (a) A single row of electrodes supported by an overhead cable which in turn was suspended between single steel towers at each bank, and, (b) a submerged lateral electrode placed on the stream bottom downstream from the suspended electrodes and traversing the entire stream width (Fig. 9). The row of suspended electrodes consisted of 118 elements of 1/2-inch standard galvanized pipe, spaced on 4-inch centers, which were hung by short wire rope hangers from a channel iron rail. The spacing between electrodes could be increased by 4-inch increments for test purposes. Electrode lengths varied from 1-1/2 to 5 feet according to the contour of the stream bed.

Figure 9. Electrical barrier installed in Hibbards' Creek in 1952.

The submerged lateral electrode was formed of sections of 1-1/2 inch standard galvanized pipe strung on a length of 1/4-inch diameter wire rope. These sections were connected by means of flexible wire "jumpers", the end section functioning as one terminal of the weir. Tests were performed with this lateral electrode located either 4 feet or 8 feet downstream from the suspended elements.

At the site of this structure, Hibbards' Creek was 40 feet wide and varied from 23 to 28-1/2 inches in average depth during the test period. The array was installed directly across the stream at a 90-degree angle to the direction of flow. No trapping mechanism was installed with this device. It was tested solely as a barrier to lamprey and fish migrations. 4/

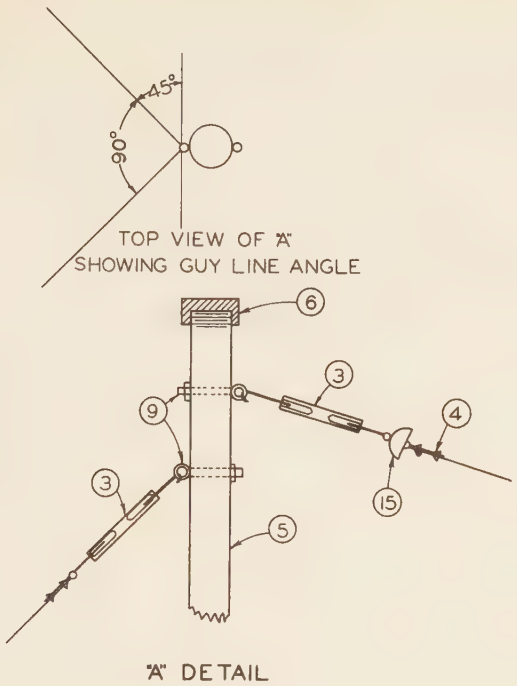
4/ The mechanical structure of the Hibbards' Creek electrical barrier and that of the Carp Creek electrical barrier which is described subsequently is very similar to that of certain electric fish screens manufactured by the Burkey Electric Fish Screen Company of Hollywood, California.

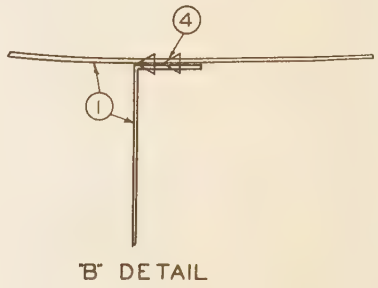
The Hibbards' Creek installation was operated as a uniform field barrier. In all tests the ground or neutral side of a 110 VAC line was connected to the submerged lateral electrode. The suspended row of electrodes was then connected to the ungrounded side of the 110 VAC line.

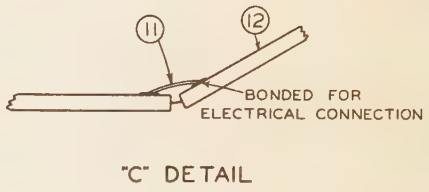
Commercial line power for operation of the barrier, floodlights, and utility lights was carried from a distribution transformer into a kilowatt-hour meter and through the fuse and switch boxes to the electrode connections. No emergency or standby source of power was provided.

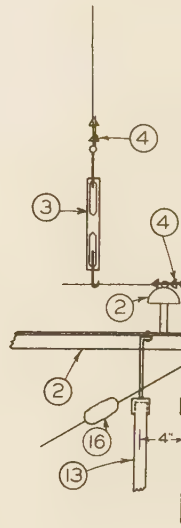
(4) Carp Creek electrical barriers.--The principal electrical barrier tested in Carp Creek was very nearly identical with that installed in Hibbards' Creek (Figs. 10 and 11). It differed in that the suspended electrodes were made of 1/2-inch O. D. thin-walled conduit and in the somewhat smaller size of the array. Carp Creek was 35 feet wide at the point of installation and varied from 9 to 14 inches in average depth during the period of operation. The array likewise was 35 feet in overall length.

Figure 10. Electrical barrier installed in Carp Creek in 1952 with upper and lower checking weirs.









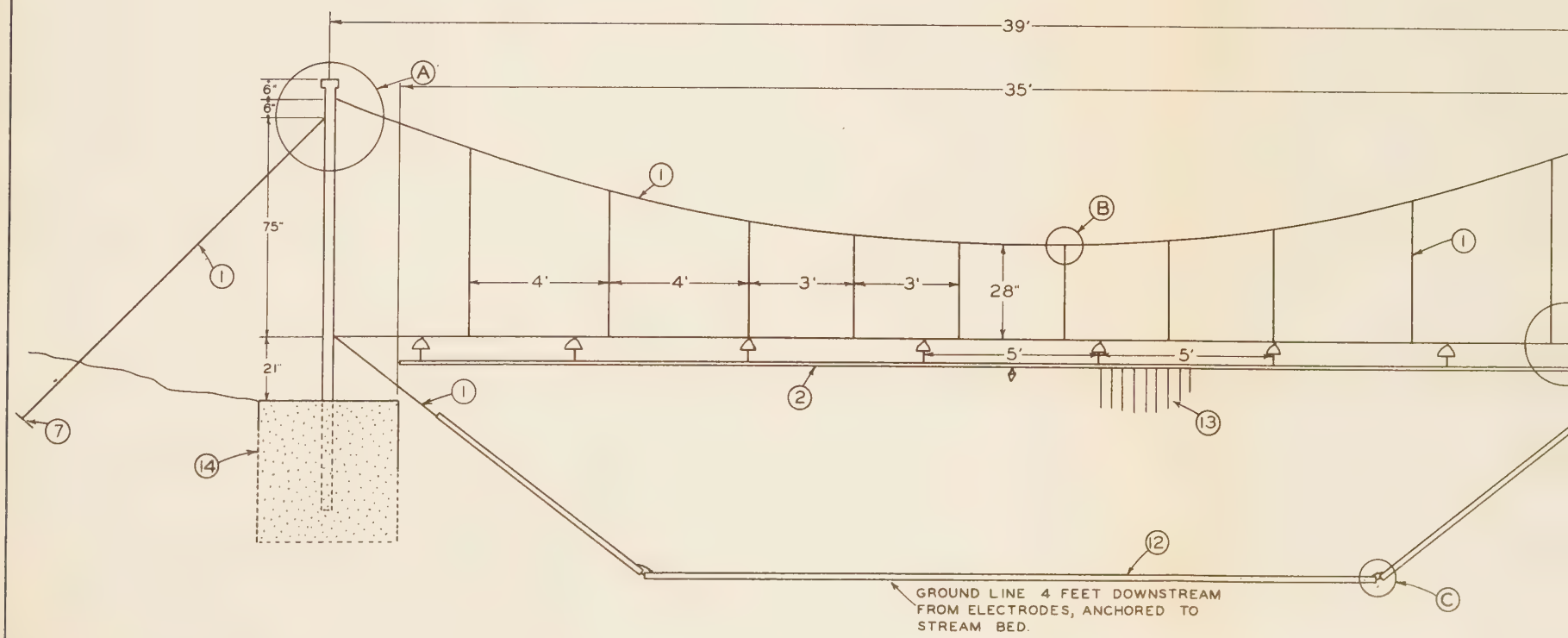


Fig. 11--Drawing of electrical barrier installed in Carp Creek in 1952.

Electrical circuitry was the same as at Hibbards' Creek (Fig. 12). The power source at Carp Creek, However, was similar to that employed at the Squaw Creek site. Two gasoline-engine driven generators of 2,000 watt capacity provided normal supply and standby power.

In addition to the installation described above, a modification of this barrier was also tested in Carp Creek. This was an extremely simple affair consisting of two lengths of 1-1/2 inch diameter galvanized iron pipe placed on the stream bed, parallel to each other, and set at an angle of approximately 90 degrees to the direction of stream flow. The spacing between these two submerged lateral electrodes was 10 feet. Power was provided by the generator source described for the principal electrical barrier installed in the stream.

Operation and testing procedures

(1) Use of checking weirs

Portable-type, mechanical weirs and traps were installed as checking structures at the four experimental sites both above and below the electrical devices (Fig. 10). Details of the method of construction of these mechanical weirs and traps have been described by Applegate and Smith (1951). During the conduct of the various experiments, the contents of the downstream checking weir-trap were removed and counted daily or twice daily. Lampreys and fish were then placed upstream above the lower weir into the test area. Daily records were kept of the numbers of lampreys and/or fish caught in the electrical weir-trap or killed in the electrical field; these data were then analyzed in their relation to the particular experiment in progress. Routine inspections of the checking weir and trap above the electrical device substantiated visual observations as to nature and extent of escapement through the electrical barrier (Fig. 13).

(2) Physical measurements

Daily records of water temperature, water level, and weather conditions were maintained at each installation. Routine records were made, at varying time intervals, of water velocity (at electrical weir site), and dissolved solids content and pH of the water. Water levels were read from staff gauges installed at each site. Water velocities were determined by one of several conventional methods with a Price current meter. Total dissolved solids present in the water was obtained with a

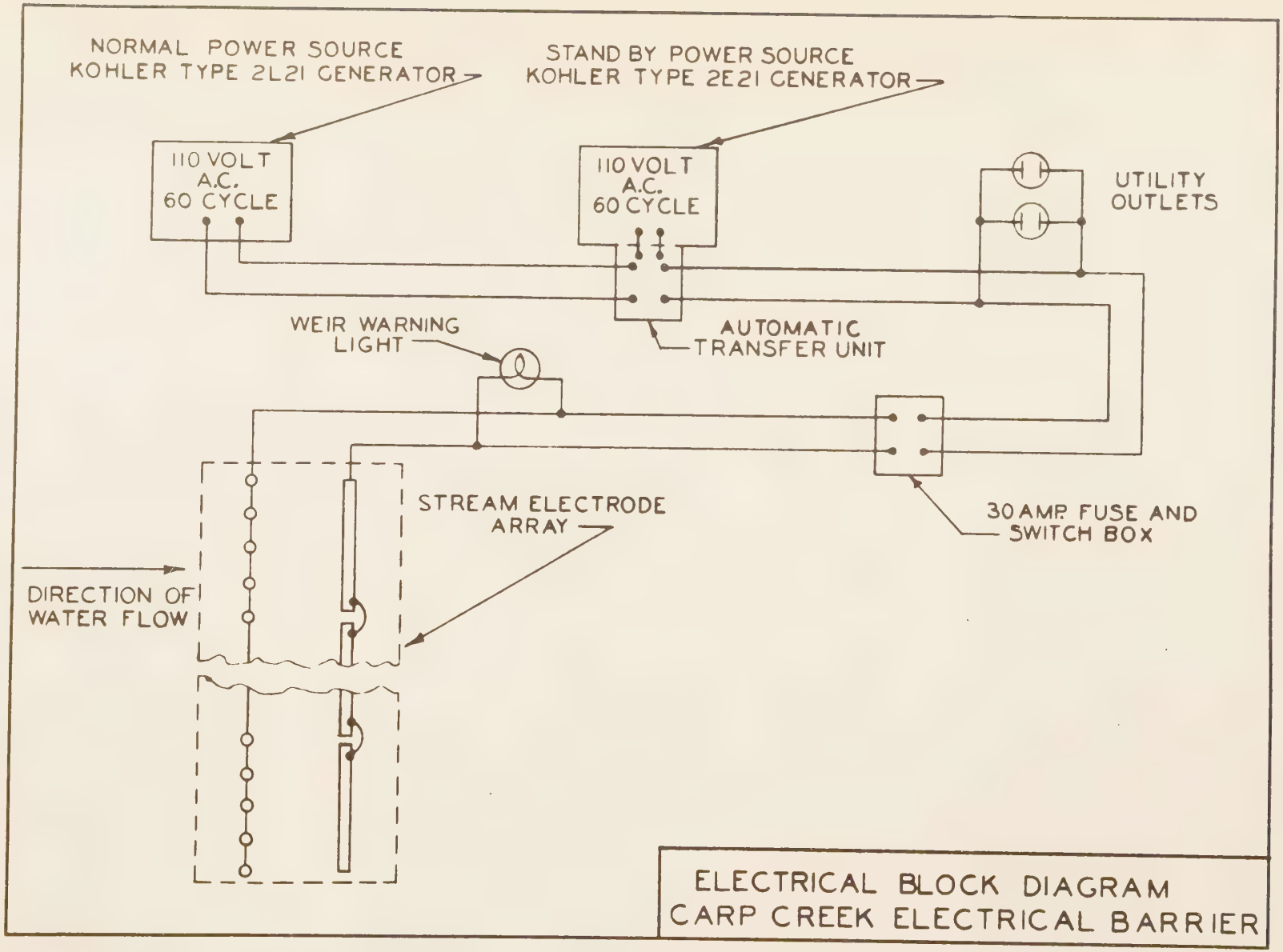


Fig. 12--Electrical block diagram of electrical barrier installed in Carp Creek.

Figure 13. Observer recording behavior of fish and lampreys below and within the electrical fields in the water.

Nalcometer, an instrument manufactured by the National Aluminate Corporation, which gave readings directly in parts per million or grains per gallon; pH readings were obtained with a Hellige comparator set.

(3) Electrical measurements

Power consumption.--Frequent measurements of power consumption were made at each of the electromechanical weir sites in order to correlate water level with power in watts drawn by the particular array under test. These measurements were also valuable in the establishment of operating cost figures for a given type array under given physical conditions. Electrical current measurements were made by means of a Pyramid Instrument Company, Model A6 "Amprobe". This device, a clip type AC ammeter, enables the operator to measure the current in the

electrical weir lead wires without cutting into or connecting directly to these wires. This instrument also contains a voltmeter circuit which may be used to measure voltages across the electrode rows of the weir.

The power consumption of the uniform field barriers is the product of the current in amperes (in the ungrounded line to the weir) and the voltage across the weir. In the incremental field barriers, two power measurements must be made; one of the power supplied to the upstream half of the weir and one of the power supplied to the downstream half of the weir. The "upstream" power is the product of the amperes measured in the "A" row of electrodes and the voltage measured between rows "A" and "B". "Downstream" power is determined in a similar manner; it is the product of "C" row amperes and the voltage between rows "B" and "C". The total power input to the weir is then the sum of the "upstream" power and the "downstream" power in watts. Power consumption will be found to vary directly with such factors as applied voltage, water level, electrolytic content of the water, and the ratio of water resistivity to stream bottom resistivity.

Voltage gradients.--Readings of water voltage gradients taken within the energized field of an electrical weir provide the most reliable measure of its effectiveness, once the blocking or lethal voltage gradient has been established. Voltage gradient measurements at the various experimental sites were made with a high impedance vacuum tube voltmeter, General Radio Model No. 727-A, used in conjunction with a specially designed water voltage gradient probe (Figs. 14 and 15). This instrument permits the operator to determine the direction of maximum current flow through the water medium at any point, and in addition, the R.M.S. value of the voltage gradient producing this current flow. The measuring electrodes of the voltage gradient probe are spaced three inches apart; therefore, readings observed on the vacuum tube voltmeter are divided by three to obtain the voltage gradient in volts per inch. This instrument was used extensively to measure voltage gradients produced in each of the various tests that involved changes in voltages, electrode diameter, or electrode spacing.

In general, between 9 and 20 readings were taken in the test of an electrical weir depending on its type. At the Carp Creek and Hibbards' Creek devices, the most significant locus of voltage gradient measurement was considered to lie at the midpoint of a line perpendicular to both the lateral, ground electrode and the line of suspended electrodes and passing midway between two adjacent suspended electrodes. The average value of three such readings, expressed in volts per inch, constitutes the "arbitrary minimum voltage gradient" subsequently referred to for this type of array. In the multiple-row, suspended electrode systems such as those operated in the Kewaunee River and Squaw Creek locations, the point

Figure 14. Checking voltage gradients within electrode array with probe and vacuum tube voltmeter.

selected for representative measurement lay midway on a straight line between an electrode in the upstream ("A") row and either of the two electrodes nearest it in the center ("B") row. The average value, expressed in volts per inch, of four such readings taken in the area between two adjacent "A" row and the nearest three "B" row electrodes was used as a representative figure of the "minimum voltage gradient" produced in the particular array being tested. All voltage gradient measurements described here were taken at midwater depth (halfway between surface and bottom) with the probe terminals in a horizontal plane and oriented for maximum voltage reading at the specified point of measurement.

The voltage gradient probe is, in addition, an effective tool for the detection of weak spots, i.e., areas of less than desired voltage gradient where escapement might result. When electrically shielded traps are used in conjunction with an electrical weir, it is possible to

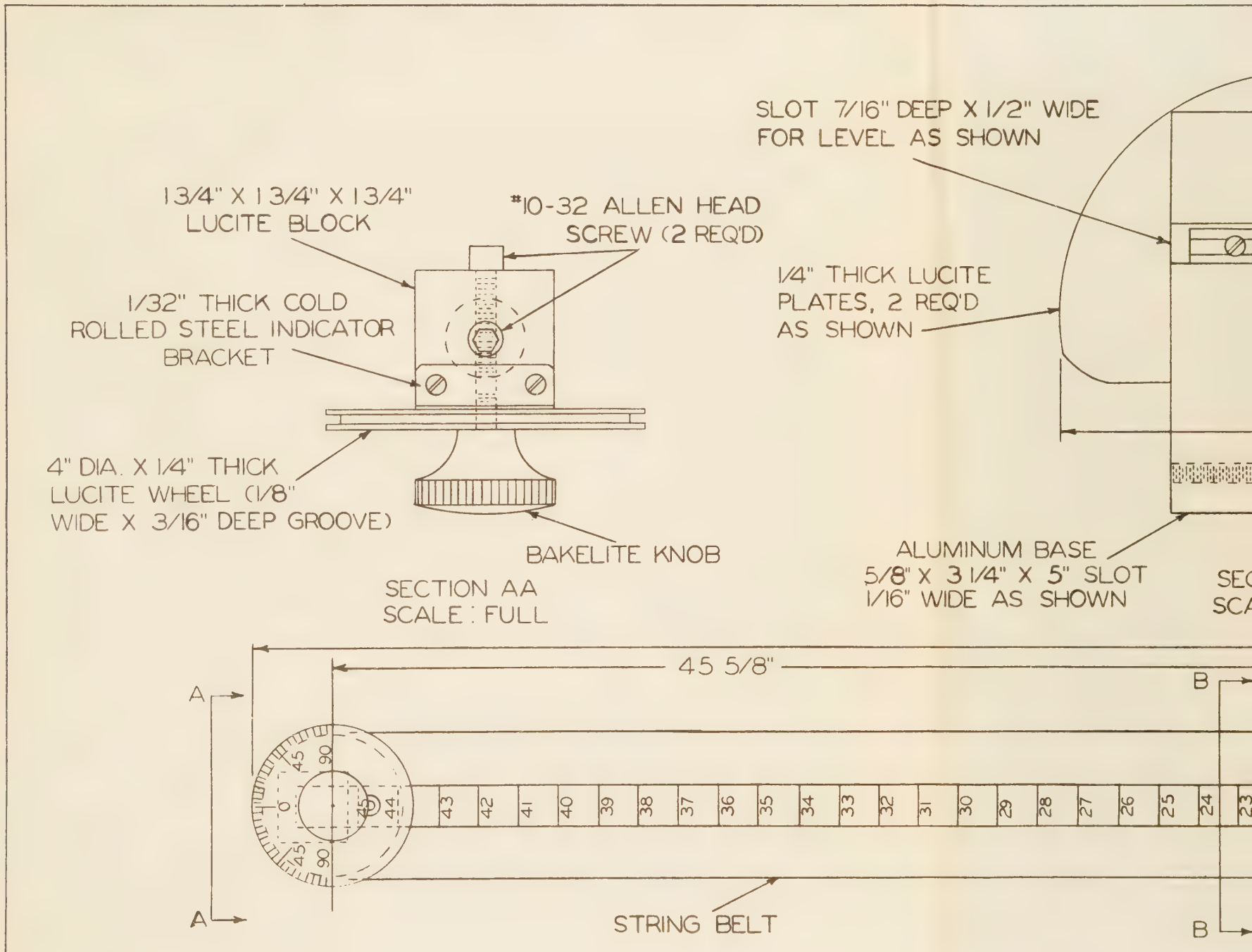


Fig. 15--Drawing of vol

determine the effectiveness of the trap shielding by measurement of the voltage gradients within, and at the mouth of the trap. The maximum voltage gradient allowable at these points for the effective operation of such traps has been determined to be in the order of 0.2 volt per inch.

Bottom resistance measurements.--At the time when these experiments were begun, it was reasoned that the resistivity of the stream bed, if somewhat lower than that of the stream water, could cause a considerable dissipation of energy with resultant weakening and distortion of the electrical fields. In order to determine the relative values of stream water and stream bed resistances at the experimental sites, a resistance probe was constructed. This device consisted simply of two pointed steel rods, 12 inches long and 7/32-inch in diameter, which were mounted on a piece of waterproofed hardwood, parallel to each other and spaced 12 inches apart. The upper halves of the rods were insulated with rubber tubing and household cement so that only the lower 6-inch section of each rod was left exposed (Fig. 16). A suitable handle affixed to the top of this assembly permitted it to be forced into the stream bottom to a depth of 6 inches or more. Two insulated wires, one to each rod, were connected to the 24 volt winding of a 110 to 24 volt, 20 watt, isolation transformer. With 24 volts AC applied to the probe, a relative measure of the resistance of the water or stream bed could be determined by dividing the voltage across the probe by the current flowing through the probe ($R = E/I$). The small AC currents occurring in these measurements were best determined by reading the voltages across a 10 ohm resistor connected in series with one of the probe leads. This voltage, when divided by ten gave the current in amperes in the probe. Precise measurements of the voltage used in determining relative resistance were made with a General Radio, Type 727-A vacuum tube voltmeter.

In making resistance measurements at the experimental sites it was found generally that readings taken at three or four points across the stream did not differ widely. Resistance measurements were first taken in the water with the rods submerged but held clear of the bottom. Where the nature of the bottom materials permitted, the probe was then forced into the bottom to the full length (12 inches) of the metal rods, and another measurement of resistance was taken. Where this procedure was not possible due to concentrations of large rocks, penetration of the bottom to a depth of only 6 inches, the length of the exposed metal rod, provided indicative readings.

Electrode effectiveness.--A series of tests were conducted in the laboratory for the purpose of determining the most desirable metal and material for use as electrodes in electromechanical sea lamprey weirs where relatively large numbers of such elements must be employed. The tests

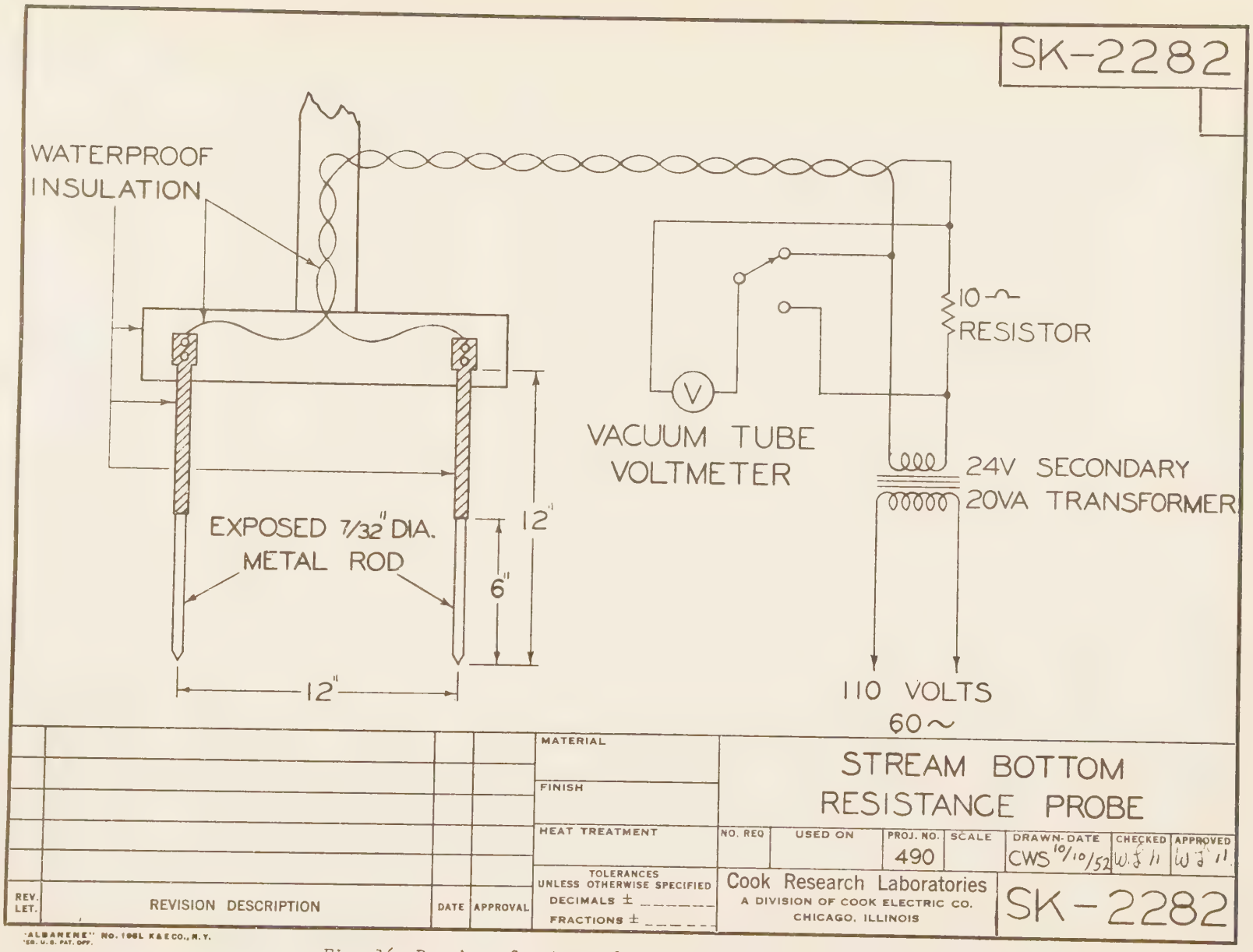


Fig. 16--Drawing of water and stream bed resistance probe.

were restricted to metals and materials of generally low cost and ready availability on the market.

The electrode tests were conducted in a concrete tank equipped with an insulating liner. The particular two electrodes used in any one test were suspended vertically into the center of a 37-inch-wide x 17-foot-long tank which was filled to a depth of 23 inches with water pumped from Lake Huron. The spacing between round electrode axes was held constant at 4 feet. All round electrodes tested were suspended in a vertical plane passing through the long axis of the tank and immersed to a depth of 12 inches. Flat electrodes (6-1/4 inches wide) were hung from the same suspensions but in two parallel planes spaced 4 feet apart and both perpendicular to the long axis of the tank; they likewise were immersed to a depth of 12 inches.

The voltage gradient probe described earlier in this section was suspended midway between the electrodes so that its terminals lay 6 inches beneath the water surface at the intersection of a vertical plane passing through the long axis of the round electrodes, the vertical center lines of flat electrodes, and a horizontal plane parallel to the surface.

A variable transformer, powered by a 110 volt AC line, was used to control the output voltage of a 1 : 1 ratio isolation transformer. The secondary or output voltage of this transformer was fed into the two electrodes under test and was held constant at 50. The voltage gradient as measured across the terminals of the probe in a particular test was used as the criterion of the effectiveness of the electrodes used.

Summary of results in 1952

(1) General

The electromechanical weirs and traps as initially installed in the Kewaunee River and Squaw Creek effectively killed, or diverted and trapped, all sea lampreys moving upstream; they continued to function efficiently as reductions in electrode systems and changes in circuitry were made until deliberately altered so as to fall below the threshold of 100-percent effectiveness. Mortality among simultaneous fish runs meeting the electrical fields of these devices was negligible. Unlike the similar device installed in the Ocqueoc River in 1951, these structures caused no significant blockade of migrant fishes. Such migrants "led" well along the fringe of the electrical field and readily entered the electromechanical weir-traps.

The electrical barriers as installed in Hibbards' Creek and Carp Creek effectively blocked the movement upstream of all sea lampreys and other migrant fishes. They likewise continued to function efficiently as reductions in numbers of suspended electrodes were made until they were deliberately rendered ineffective.

Several simplified structures were developed from both the electromechanical weirs and traps and the electrical barriers which, in general, require less physical plant and power input than the pilot model structures installed in 1952. These developments are embodied in three recommended designs for electrical sea lamprey control devices which are presented in the final section of this report.

Although considerable effort has been directed at determining effective electrical field patterns and voltage gradients (for blocking sea lampreys) and at improving the mechanical design and electrical circuitry of developed structures, comprehensive and detailed investigations of numerous variables having only a nominal effect on the operating effectiveness and efficiency of the devices have not been made. Exploratory researches only in such matters as the effect of varying water and bottom resistivity on power drain or the effect of extremes in water level on power requirements were conducted with the intent of providing "yardsticks" or guides in designing equipment to fit specific streams in the immediate future. Because of the urgency of the problem, a sea lamprey control program, when effected, must operate as it grows. In such circumstances, ample opportunity will present itself to evaluate further the effect of these variables on the functioning of electrical mechanisms used.

Specific findings obtained during the 1952 season are incorporated in Sections 2 to 8 following.

(2) Minimum voltage gradient requirements

Experimentation in 1952 substantiated the fact that a minimum voltage gradient of 0.75 volt per inch must exist in the water on a line between electrodes if the electrical field is to effect a complete block of the lamprey run. This statement applies specifically to gradients existing between electrodes of the center and upstream rows comprising the upper half of an incremental field barrier, and between electrodes of any two adjacent rows of a uniform field barrier created by either a 3-row or 2-row electrode system. It applies further to any 2-row electrode system regardless of whether both rows consist of suspended electrodes or whether one row is suspended and the other is replaced by a single, lateral submerged electrode. It was also substantiated that if an adequate margin of safety is desired, the minimum voltage gradient between the aforementioned electrodes must be at least 1.0 volt per inch.

The above minimal gradients have been established on the basis of an electrical field created in depth by a system of electrodes distributing the electrical field over at least 4 feet of stream length (i.e., center and upstream rows of incremental field barrier, or any two rows of uniform field barrier). A simple system of electrodes (i.e., one row with every other electrode wired alternately to grounded and ungrounded sides of a 110 VAC circuit) would require much greater voltage gradients particularly if located in sluggish waters. Furthermore, it is extremely doubtful whether such a single row structure utilizing practical input voltages would provide a completely lamprey-tight barrier.

It seems pertinent to point out here that migrant sea lampreys are not only highly resistant to electrical shock 5/ but display little or no avoidance reaction to an electrical field in the water. Whereas other migrant fishes react sensitively to very weak gradients at the fringe of an electrical field (and tend to avoid same), the lampreys show no such reaction. Characteristically, the lamprey swims into a field of increasing intensity, laboring against oncoming paralysis until complete paralysis prevents any muscular movement whatsoever. This resistance to electrical stimulation, the determined nature of their migration, and their ability to swim very rapidly at least over short distances, would as a rule permit some escapement through a barrier creating only a relatively thin electric field in the water.

5/ Applegate, Vernon C. and William L. Stahl. Use of electricity in the control of sea lampreys: Experimental electrocution of downstream migrants. MS.

(3) Electrode array pattern, circuitry, and power requirements

Experimentation with the several devices indicated that a variety of electrode array patterns were effective at low power demands provided the voltage gradients produced in the water were not below the minimum of 0.75 volt per inch discussed previously.

Multiple-row, suspended electrode systems used with the electromechanical weirs and traps were readily adaptable for creating either incremental or uniform electrical fields. Two methods of producing incremental fields were tested at the Kewaunee River device of which the first proved to be more economical in power requirements than the second.

In the first method, where incremental fields were produced by maintaining equal spacing among all electrodes of all rows and applying one-half the AC line voltage (110) across the "B" and "C" rows, the following results were obtained (interval between rows of electrodes in the array held constant at 4 feet in all tests):

(a) With a spacing of 4 feet between electrodes in each row, minimum voltage gradients between electrodes of the "A" and "B" rows in excess of 0.75 volt per inch were present in the water and sea lampreys were unable to penetrate the upstream half of the array. Furthermore, many lampreys which penetrated the lower half of the array where voltage gradients were reduced were completely immobilized and, where they settled to the bottom within the array, were killed by suffocation. Average water depth at the weir site during this test was 12.5 inches; 1,533 watts were required to energize the device.

(A similar test conducted at the Squaw Creek installation with smaller diameter electrodes set on 3-foot centers in rows spaced 3 feet apart produced identical results. This array, considerably smaller than that in the Kewaunee River, drew only 191 watts when the average water depth at the weir site was 10.7 inches).

(b) With a spacing of 6 feet between the electrodes of each row, minimum voltage gradients between elements of the "A" and "B" rows averaged 0.70 volt per inch. Sea lampreys were still unable to traverse the upstream half of the array. Occasional individuals, however, were observed to penetrate this latter area quite deeply although none escaped through the field. Had water velocities within the array been less than the minimum 1.35 f.p.s. existing during all these tests, it is extremely doubtful whether a complete blockade of the sea lamprey run would have been accomplished with this electrode spacing. A subsequent test indicated that even at these water velocities, any greater spacing of electrodes within a row permitted lampreys to escape through the electrical

field. Although average water depth at the weir site during this test had increased to 15.1 inches, only 1,192 watts were required to energize the array.

(c) With a spacing of 8 feet between the electrodes of each row, minimum voltage gradients between elements of the "A" and "B" rows averaged 0.64 volt per inch. Sea lampreys were now observed to penetrate and pass through the entire electrical field and continue their journey upstream. Average water depth at the device during this test was 15.1 inches; 960 watts were required to energize the array.

In the second method, in which incremental fields were produced by removing every other electrode from the "C" row while at the same time the full AC line voltage was applied across the "A" and "B" and the "B" and "C" rows, the following results were obtained from the single test performed (4-foot interval between rows of electrodes in the array):

(d) With electrodes of the "A" and "B" rows set on 4-foot centers and those of the "C" row set on 8-foot centers, minimum voltage gradients between electrodes of the "A" and "B" rows were in excess of 0.75 volt per inch. A complete blockade of the sea lamprey run was effected comparable to that created in Test (a) above. Average water depth at the weir during this test was 15.9 inches; 2,425 watts were required to energize the array.

Comparison with Test (a) above indicates that under comparable stream conditions, power requirements for developing an incremental field by this method are approximately one-third greater than for that developed by the first method discussed.

Uniform electrical fields were produced with both 3-row and 2-row suspended electrode systems by applying the full AC line voltage (110) across the "A" and "B" and the "B" and "C" rows of the 3-row system or simply across the two rows of a 2-row system. Where the 3-row electrode system was tested at Squaw Creek, the following results were obtained (interval between rows of electrodes in the array was 3 feet):

(e) With a spacing of 3 feet between electrodes in each row, minimum voltage gradients between electrodes of the "B" row and those of the "A" and "C" rows averaged 0.86 volt per inch. Sea lampreys were unable to penetrate any portion of the array. Average water depth at the weir site during this test was 8.9 inches; 197 watts were required to energize the device.

Where the 2-row electrode system was tested in the Kewaunee River, the following results were obtained (interval between the two rows was 4 feet; in effect, only the "B" and "C" rows of the original 3-row installation were used):

(f) With a spacing of 4 feet between electrodes in each row, minimum voltage gradients between electrodes of the two rows averaged 0.98 volt per inch. Sea lampreys were unable to penetrate the array. Average water depth at the weir site during this test was 10.5 inches; only 1,192 watts were required to energize the array.

This was the simplest and most economical multiple-row, suspended electrode system developed during the present tests which effectively blocked a sea lamprey run. Although extremely effective in a relatively shallow location in the stream where water velocities were swift, the general utility of this simple array has not been determined. It remains to be demonstrated whether it will function with equal effectiveness in deeper and more sluggish water.

A nominal disadvantage in the utilization of uniform electrical fields with these arrays is that few lampreys are killed by the device. Meeting first an electrical field of paralyzing intensity rather than the zone of reduced intensity characteristic of the incremental electrical field, the lampreys cannot penetrate the area within the electrode array. Stunned at or below the lower-most row of electrodes, they are carried out of the electrical field by the water current and recover rapidly.

In all tests of incremental and uniform electrical fields, runs of other fishes, particularly suckers, "led" well along the "fringe" field (below the lowermost row of electrodes) and entered the weir-trap with little or no observed mortality or blocking effect. This represents a marked improvement over the similar device installed in the Ocqueoc River in 1951. The improved efficiency of the Kewaunee River and Squaw Creek installations in capturing migrant fishes for transfer upstream is attributed primarily to careful location of the electrical blocking field and weir-trap in each stream. Weir-traps were placed directly in the path followed by the majority of migrant fish swimming upstream. In the Kewaunee River at the site chosen for the installation this path happened to lie very close to one bank; at the Squaw Creek site most fish movement occurred in midstream. Electrode arrays were then installed so as to provide "leads" to these points for those fishes traveling elsewhere across the width of the stream. The tendency of the earlier Ocqueoc River device to block rather than "lead" and capture migrant fishes was undoubtedly due to improper location of the weir-traps which were adjacent to the stream banks rather than in midstream where the majority of fish movement occurred at that particular site.

Another factor that contributed to the greater success of these devices in "leading" and trapping fish was the rapid water velocities occurring at the loci of installation (Kewaunee River: range - 1.35 to 1.54 f.p.s., average - 1.41 f.p.s.; Squaw Creek: spot reading - 1.13 f.p.s.). The swifter waters in the riffle areas over which the arrays were installed discouraged or prevented fish from penetrating the "fringe" field into areas of greater electrical current density where the alternating current fields would tend to disorient them.

It was evident further from these tests that where sufficiently rapid water velocities exist as at the Kewaunee River and Squaw Creek sites, the use of the more complex incremental electrical fields to create a "warning" zone (to fishes) is not necessary in order to effect satisfactory protection and salvage of fish runs. The use of "warning" zones (through the application of incremental electrical fields) still appears desirable, however, where the electromechanical devices are installed in deep and sluggish stream locations.

Arrays consisting of a single row of suspended electrodes and a horizontal, submerged electrode formed effective barriers to all lamprey and fish movement with intervals as great as 6 feet between the suspended electrodes when the horizontal, submerged electrode was placed 8 to 10 feet downstream from the suspended elements. Results obtained with this type of array in Hibbards' Creek were as follows (power applied to array - 110 VAC):

Test number	Interval between horizontal, submerged electrode and line of suspended electrodes (feet and inches)	Interval between suspended electrodes (feet and inches)	Arbitrary minimum voltage gradient (volts per inch)1/	Average water depth at installation (inches)	Power requirements (watts)	Effective barrier to lampreys and fishes
1	4'-0"	2'-0"	1.54	26.6	1,790	Yes
2	8'-0"	0'-4"	1.10	27.0	2,125	Yes
3	8'-0"	2'-0"	0.85	23.5	1,260	Yes
4	8'-0"	4'-0"	0.67	25.1	1,041	Yes
5	8'-0"	6'-0"	0.63	24.5	728	Yes
6	8'-0"	8'-0"	0.54	25.5	685	No
7	8'-0"	10'-0"	0.53	25.0	654	No
(horizontal submerged electrode placed upstream from the suspended electrodes)						
8	4'-0"	2'-0"	1.36	27.5	1,696	Yes

1/ See discussion, page 24.

Results obtained with a similar array in Carp Creek were as follows (power applied to array - 110 VAC):6/

Test number	Interval between horizontal, submerged electrode and line of suspended electrodes (feet)	Interval between suspended electrodes (feet and inches)	Average water depth at installation (inches)	Power requirements (watts)	Effective barrier to lampreys and fish
1	10'-0"	0'-4"	16.5	640	Yes
2	10'-0"	1'-0"	11.0	608	Yes
3	10'-0"	2'-0"	10.0	576	Yes
4	10'-0"	3'-0"	12.5	532	Yes
5	10'-0"	4'-0"	12.0	456	Yes
6	10'-0"	8'-0"	12.0	264	No

These devices in Hibbards' and Carp Creeks were tested solely as simple barriers to the upstream movements of lampreys; as such, they functioned effectively and inexpensively with a minimum of installed equipment.

The use of this simpler electrode array to supplant the more complex and expensive multiple-row, suspended electrode systems of the electromechanical weirs and traps appears feasible. Until further investigations have been made, however, such use in electromechanical devices should be restricted to sites where the water is comparatively shallow and where relatively rapid water velocities, at least in excess of 1.5 f.p.s., exist. Observations at Hibbards' Creek where deeper and very sluggish water occurred (static to 0.52 f.p.s.) at the electrical barrier site indicated

6/ Records of voltage gradients were faulty and hence are not given here.

that the device caused some mortality among migrant fishes when the horizontal electrode was located downstream from the vertical elements. The character of the electrical field established between the vertical suspended electrodes and the horizontal submerged electrode is such that where the installation is situated in deep, sluggish water, migrant fish swimming near the surface can cross above the horizontal electrode. Approaching closer to the vertical electrodes they become stunned and are killed when they fall to the bottom inside the horizontal electrode in the strongest area of the electrical field. This mortality did not occur at Carp Creek where shallow water and swifter stream velocities existed.

Evidence as to the amount of fish mortality resulting when the horizontal, submerged electrode was placed upstream from the vertical elements was not obtained during the single test conducted at Hibbards' Creek. Fish migration in the stream had ceased when this test was in progress. However, the behavior of the lampreys during this test suggested that fish mortality might be minimal with this electrode arrangement.

A test conducted in Carp Creek with an array consisting of only two horizontal, submerged electrodes placed parallel on the stream bed indicated that under restricted conditions a barrier to lamprey and fish movement could be effected with this simple equipment. With electrodes placed 10 feet apart at a point where the water averaged 12 inches deep, 110 VAC was applied across the elements; sea lampreys were unable to penetrate this electrical barrier. Only 480 watts were required to energize the device.

Further experimentation with this device is necessary in order to establish its working limits. With this electrode arrangement, the area of lowest electrical field strength and most likely point of escapement of lampreys through the barrier is at the surface of the water directly above a point midway between the electrodes. At any fixed input voltage, the strength of the electrical field at this weakest point is a function of the distance between electrodes and the water depth. Ultimate use of the device will be restricted by the maximum stream depth at which satisfactory voltage gradients can be established at this weakest point when a given optimum spacing between electrodes for an input of 110 VAC is used.

(4) Electrode size, conformity, and efficiency

It has been concluded that the most suitable electrode materials for use in sea lamprey electrical weirs are the following in the order presented: (a) 1/2-inch diameter thin wall conduit, rough surface, (b) 1/2-inch diameter thin wall conduit, smooth surface, (c) 1/2-inch

diameter galvanized pipe. This conclusion is based on unit costs of the materials tested and the results of electrical tests conducted as described in a preceding section. The materials selected for the tests were those of generally low cost and ready availability on the market. Measurements of midpoint voltage gradients and values for relative electrode effectiveness are presented in Table 1. The latter values are based on a figure of 100 percent assigned to the midpoint voltage gradient produced by the 2-inch diameter, galvanized pipe electrode (R-4). This electrode was selected as the standard of comparison in these tests simply because it produced the highest midpoint voltage gradient of those round electrode types tested. Flat electrode materials were tested for comparison with round electrode materials as a matter of academic curiosity only, since mechanical considerations (would seem to) preclude their use in sea lamprey weirs. Where known, unit cost of the round electrode materials was used in the determination of a "cost-efficiency" figure, the magnitude of which was the criterion applied to the final selection of the three most suitable electrode types. Surface dissimilarity which is apparently the only difference among the electrical conduit electrodes (R-6 to R-9, Table 1) is probably attributable to minor variations in the manufacturing processes employed. That these differences in type of surface account for different efficiencies was indicated in the test results in that the rough surfaced conduit, having a greater surface area than the smooth surfaced material of the same nominal diameter, exhibited the higher relative effectiveness. It should be stated here that the differences in effectiveness of the various round electrodes tested are not so great but that any of them might be used in arrays with necessary minor adjustments in row and electrode spacing to compensate for variations in effectiveness. In consideration of the desirability of locating electrical sea lamprey weirs in riffle areas where high water velocities may exist and cause considerable electrode deflection, pipe electrodes offer a distinct advantage over those made of electric conduit or thin-wall aluminum tubing. Galvanized steel pipe, having a considerably greater weight per unit of length than these other materials, will undergo less deflection for a given water velocity, thereby limiting fluctuations in the intensity of the electrical field. Another probable advantage (though not yet proven in field tests) in the use of galvanized pipe is that of longer protection against complete corrosive deterioration by virtue of its greater wall thickness.

(5) Electrode mounting

All of the suspended electrode systems tested proved to be entirely satisfactory. In spite of the increased size of the physical structure required, they were a considerable improvement in nearly all respects over the ground-mounted system installed in the Ocqueoc River in 1951. With the suspended systems, localized and general losses of

Table 1. Relative electrode effectiveness and cost efficiency values for common electrode materials

Electrode Type	Electrode Description	Midpoint voltage gradient (VAC/inch)	Relative electrode effectiveness (R-4 = 100 o/o)	Cost per foot of electrode materials (dollars) 1/	Cost-efficiency value (Relative effi./ unit cost)
F-1	1/2-in., galv. metal hdwe. cloth	0.716	99.5	...	...
F-2	1/4-in., galv. metal hdwe. cloth	0.750	104.3	...	...
F-3	1/16-in., thick galv. metal sheet	0.766	106.5	...	...
F-4	1/32-in., thick copper sheet	0.772	107.3	...	...
R-1	1/2-in., nominal diam. galv. pipe	0.560	77.8	.15	519
R-2	3/4-in., nominal diam. galv. pipe	0.599	83.4	.18	463
R-3	1-in., nominal diam. galv. pipe	0.616	85.6	.25	343
R-4	2-in., nominal diam. galv. pipe	0.719	100.0	.52	192
R-5	2-in., O.D., thin wall alum. tubing	0.686	95.4	...	...
R-6	1/2-in., O.D., thin wall elec. conduit, rough surface	0.516	71.7	.12	598
R-7	1/2-in., O.D., thin wall elec. conduit, smooth surface	0.506	70.4	.12	587
R-8	3/4-in., O.D., thin wall elec. conduit, rough surface	0.583	81.0	.18	450
R-9	3/4-in., O.D., thin wall elec. conduit, smooth surface	0.579	80.5	.18	447

1/ Average price extant in 1952.

power to the stream bed were minimized through the provision of adequate clearance between distal ends of electrodes and stream bed to allow for any sagging of the electrode suspension caused by expansion of cables or settling of tower bases. Damage to, or permanent displacement of, electrodes by floating debris and mechanical damage to wiring was practically non-existent.

Hinge mountings as used in the multiple-row electrode systems and the short cable and pipe-cap hangers used in the single row and ground line systems proved to be inexpensive and mechanically sound (see "Detail" in Figs. 6 and 11). It was found to be absolutely essential that only hinge mountings be used with any multiple-row, suspended electrode system. This type of mounting restricts the movement of the electrode to a single plane of deflection (downstream) and prevents contact between electrodes of adjacent rows with resultant short-circuiting of the device. The simpler cable and pipe-cap mounting is entirely satisfactory for use with the single row, suspended electrode and ground line system since random movement and contact among the single row of suspended elements produces no damaging short-circuits.

(6) Effects of water level, water resistivity, and bottom resistivity on power drain

A direct, though non-linear, relationship exists between power consumption of an electrical weir and the water level of the stream in which it is installed, assuming water resistivity and applied voltage to be constant. Conversely, at a given water level, power consumption of such a device is directly proportional to the square of the applied voltage and inversely proportional to the water resistivity. Changes in the power demand of an electrical weir or variation in load at other points on a commercial power line will, in extreme cases, cause fluctuations of ± 6 volts on a nominal 117 volt AC line. Water resistivity, in turn, is influenced by such factors as dissolved and suspended solids content, pH, and water temperature. Frequent measurements of water level and power consumption made at each of the weir sites did not reveal the exact nature of the water level-versus-power relationship. This fact may be understood when it is realized that neither the direct effects of voltage variation nor the sometimes diverse effects of the variables governing water resistivity, could be controlled (e.g., water temperature might rise coincident with a rise in dissolved solids content, these factors having opposite influence on water resistivity). Measurements of water temperature, dissolved solids content, and pH were made at each experimental site at every possible opportunity in an endeavor to correlate these variables with power consumption. Determination of the true correlation was precluded in this case by the interaction of these variables and lack of a sufficiently large number of measurements. However, in a test conducted at the Carp Creek weir site at a constant voltage level over a period of time sufficiently

short to preclude the slightest variation in water resistivity, a simulation of water level change provided experimental data representative of the water level-versus-power relationship. These data are presented graphically in Figure 17.

Relative values of stream bed and stream water resistance were measured at the four electrical weir sites as described in an earlier section. Results indicated clearly that: (a) in these locations the ratio of stream bed to water resistance was 1.4 : 1 or greater, and (b) this ratio increased with the depth to which the resistance probe was forced into the stream bed. These findings represent highly desirable conditions for the operation of an electrical weir. Where bottom resistivity is high, excessive power loss will not occur in the stream bed because its higher relative resistance will inhibit the flow of current through it. Therefore, it is desirable to locate all electrical weirs in an area where the ratio of stream bed to water resistance is greater than 1, as measured by the method described earlier or by any comparable method.

(7) Power sources

The following three systems of electrical weir power supply, all of which proved effective and satisfactory, were tested during the course of the 1952 experiments:

System 1 (Commercial line power only): This method of operation, as tested at Hibbards' Creek, did not permit the escapement of lampreys. No known power failure occurred, and at no time did the line voltage fall to a value sufficiently low to render the barrier ineffective.

System 2 (Commercial line as normal, generator as standby power source): This system, as used at the Kewaunee River weir, was successful in maintaining continuous power. Since no line power failures occurred, the operation of the standby generator was checked frequently by manual interruption of the line power. The time interval preceding restoration of power to the weir by the standby generator was estimated to be considerably less than 1 second. This was demonstrated by the fact that the discontinuity in power was only discernible with difficulty in the slight deflection of a voltmeter connected across the weir terminals. The time interval required to transfer the electrical weir load back to the normal source of power upon its restoration was not sufficiently great to detect visually in an incandescent light bulb connected across the weir terminals. In neither case were lampreys capable of escaping through the weir in the small interval of time during which the power was broken. The standby generator, which was operated a total time of approximately 170 hours, functioned satisfactorily without breakdown or need for repairs of any kind. This generator had ample capacity for the operation of floodlights and warning lights during periods of maximum power consumption of the electrical weir.

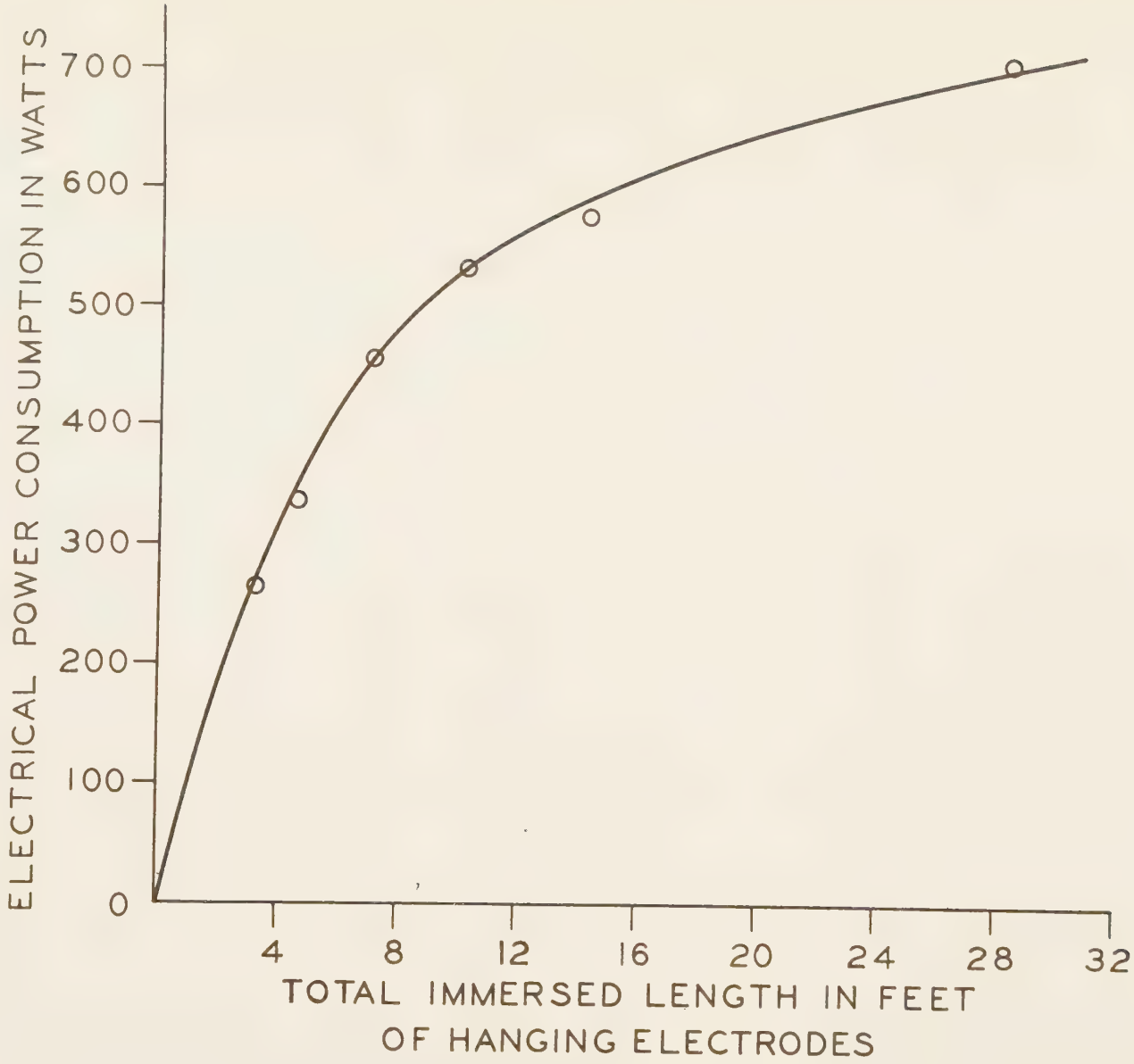


Fig. 17--Relationship of total immersed electrode surface and power consumption.

System 3 (One generator as normal, one generator as standby source of power): The Carp Creek and Squaw Creek devices were operated successfully with this method of power supply. The normal source generators supplied power at these sites throughout the conduct of the experiments with the exception of those periods during which they were stopped manually in order to test-run the standby generators. The standby generator at each site was test-run approximately 200 hours; both operated in a completely satisfactory manner without breakdown. The time interval required for the standby generators to "take over" upon interruption of the normal source generators was in both cases equivalent to that described under System 2. The power capabilities of the normal and standby generators used in System 3 were more than sufficient to supply maximum weir loads encountered.

(8) Costs of installation and operation

Installation costs for the four structures tested in 1952 were as follows:

Structure	Materials and equipment	Labor and field supervision	Operation of vehicles and construction equipment	Total
Kewaunee River electromechanical weir and trap	$1,842.91	$2,458.65	$97.63	$4,399.19
Squaw Creek electromechanical weir and trap	1,703.06	1,092.48	54.36	2,849.90
Hibbards' Creek electrical barrier	1,599.92	1,038.28	21.60	2,669.80
Carp Creek electrical barrier	1,599.92	327.73	3.49	1,931.14

Operating costs fall into two major categories - electrical power and labor. Commercial line power supplied to the Kewaunee River electromechanical weir and trap between April 23 and June 17 cost $62.70 for 1,680 KWH (kilowatt hours) used. Similar power supplied to the Hibbards' Creek electrical barrier between April 16 and June 18, 1952 cost $52.34 for 1,366 KWH used.

Power supplied to the Squaw Creek electromechanical weir and trap by 3.5 KW, gasoline-engine driven generators cost $96.85 for 1,063.2 hours of operation. Similar power supplied to the Carp Creek electrical barrier by 2 KW, gasoline-engine driven generators cost $93.41 for 840.7 hours of operation. Most useful in planning future operations are cost-per-hour figures for individual generators of different capacities. Records kept for five gasoline-engine driven generators were as follows:

Generator number	Capacity (KW)	Total hours of operation	Total cost of operation	Cost per hour of operation
6	2	778.0	$85.43	$ .11
7	2	62.7	7.98	.13
8	3.5	750.0	66.79	.09
9	3.5	313.2	30.06	.10
5	5	171.8	34.24	.20

The low cost-per-hour figures for the 3.5 KW generators indicated above do not necessarily imply that they were the most economical "size" of generator used. The figures merely reflect the fact that the power demand on these generators was well below the maximum capacity of the units during most of the period of operation. The 2 KW generators were taxed much more heavily in proportion to their capacity output. Both 2 KW and 3.5 KW power plants used were almost identical in gross size and weight. The 5 KW plant on the other hand, was a considerably larger unit. Although operated at only 19 to 49 percent of capacity output (less than the capacity output of a 3.5 KW unit), the increased size of the plant was reflected in a near doubling of the "cost per hour of operation".

Labor costs for operating traps in the electromechanical devices are not available since these expenses could not be separated from labor costs for operating checking weirs used during the tests. It was apparent, however, that approximately 2 hours of labor per day per control structure would provide satisfactory servicing. This figure includes travel time to and from the weir and is based on the assumption that the attendant would be servicing a group of such devices within a limited geographic area. It is estimated that under such circumstances direct labor costs for servicing each electromechanical weir and trap would amount to

$262.50 per season. This applies in those lake basins where the sea lamprey's spawning run season lasts an average of 3 1/2 months and is based on an average hourly rate (in 1952) for laborers of $1.25.

Recommendations

At the present time, no single electrical mechanism for general use in all sea lamprey spawning streams is recommended. In streams where simultaneous fish runs must be protected, an electromechanical weir and trap is required. Considerable care should be taken in advance to determine the primary path of upstream movement of migrant fishes at the site of installation. Weir-traps should be installed directly in this path and the electrode array "tailored" to provide "leads" to the trap.

A multiple-row, suspended electrode system is recommended where any, or a combination of, the following conditions obtain at the locus of installation:

(1) Maximum flood depths are greater than 5 feet

(2) Stream velocities are less than 1.0 f.p.s.

(3) Stream bed materials are soft or floculent

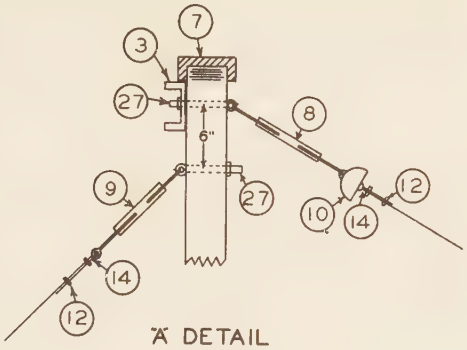
In general, a two-row electrode system creating a uniform electrical field should suffice in such locations. A recommended design for an electromechanical weir and trap of this type is presented in Figure 18.

At sites where very sluggish water exists (0.5 f.p.s. or less), observations during operation of the above device may indicate that some fish mortality results due to the ability of some migrants to propel themselves into the strongest areas of the electrical field. Should this occur, it would be desirable to alter the device to a three-row system with an incremental electrical field. Modification of the structure detailed in Figure 18 to accommodate a third row of electrodes may be accomplished as follows:

(1) Remove 5-foot, channel iron crosspiece at top of each pair of suspension towers.

(2) Replace with similar crosspiece measuring 10 feet long; crosspiece should be centered on centerline between dual suspension towers.

(3) Install suspension cables for three rows of electrodes on 4 1/2-foot centers with middle row on centerline between towers.



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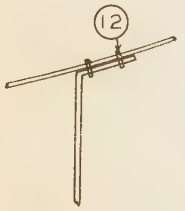

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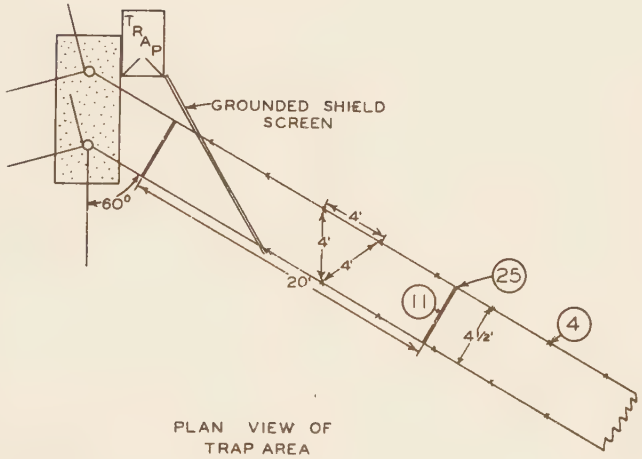
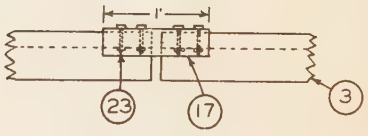


PLAN VIEW OF TRAP AREA



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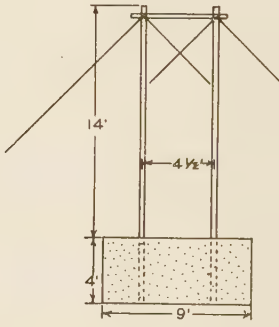
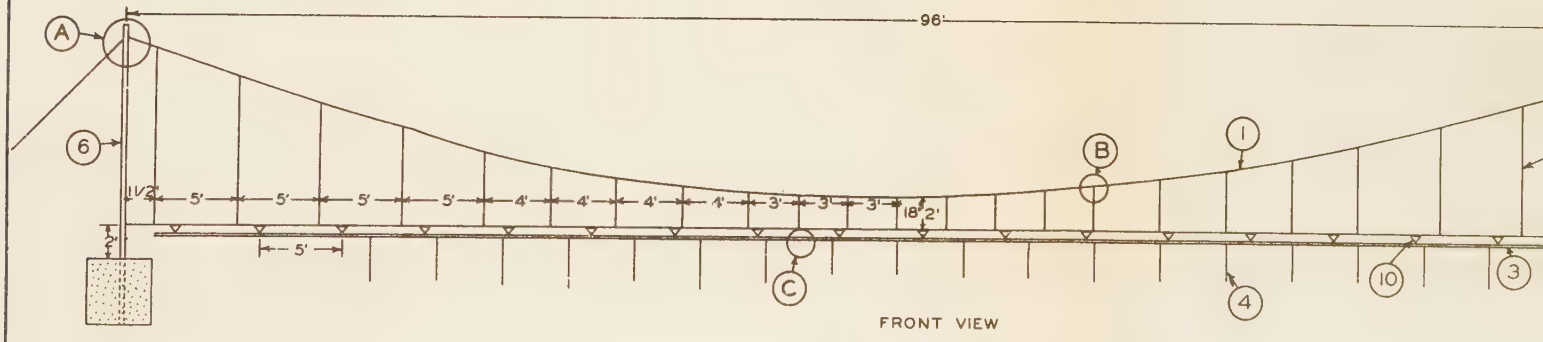


END VIEW



FRONT VIEW

Fig. 18--Drawing of recommended design of multiple-row, suspended electrode, electromechanical weir and trap.

(4) Install light channel iron crosspiece, 10 feet long, at appropriate height on each dual tower to establish anchor for horizontal cables providing alignment and direct support of the electrode array.

In stream locations where maximum flood depths do not exceed 5 feet, water velocities do exceed 1.0 f.p.s., and stream bed materials are firm, an array consisting of a single row of suspended electrodes and a horizontal, submerged electrode may be substituted for the multiple-row installation. Details of a recommended design for this type of array may be derived from the plans for an electrical barrier presented in Figure 19. Should field observations indicate that this array is causing an appreciable mortality among migrant fishes, it may prove expedient to shift the horizontal, submerged electrode to a position on the upstream side of the row of suspended electrodes.

In those sea lamprey spawning streams that have no fish runs of importance, it is recommended that simple, electrical barriers be installed. Such streams will, as a rule, be small and the array consisting of a single row of suspended elements and a horizontal, submerged electrode will be adequate for most locations. A design for an electrical barrier utilizing this type of array is presented in Figure 19. In very small tributaries, an electrical barrier may be effected by installing only two horizontal, submerged electrodes placed parallel to each other on the stream bed. A suggested design for such an installation is presented in a sketch in Figure 20. However, until the working limits of this very simple device are determined, it is not recommended that it be installed in streams having maximum flood depths greater than 2 feet at the point of installation.

All recommended designs and suggested modifications are based on the utilization of sources of power providing 110 VAC for application to the arrays. In all cases, a minimum voltage gradient of 1.0 volt per inch between specified electrode elements (as described in previous sections) should be established. Although appreciably higher than the minimum of 0.75 volt per inch required to block sea lampreys, this arbitrary minimum provides a suitable margin of protection against seasonal changes in water conductivity, losses of electrical field strength due to inadvertant grounding of distal ends of hanging electrodes, erratic field patterns created by displacement of electrodes, and other minor variables causing local or general weakening of the electrical fields.

Electromechanical weir-traps and the approaches to these traps should be thoroughly explored with the voltmeter probe to determine if these areas are adequately "cold" from an electrical standpoint. The maximum voltage gradient permissable in these areas which will not repel or stun fishes is in the order of 0.2 volt per inch. Excessive gradients can usually be reduced by increasing the size of the shunt screens (i.e.,

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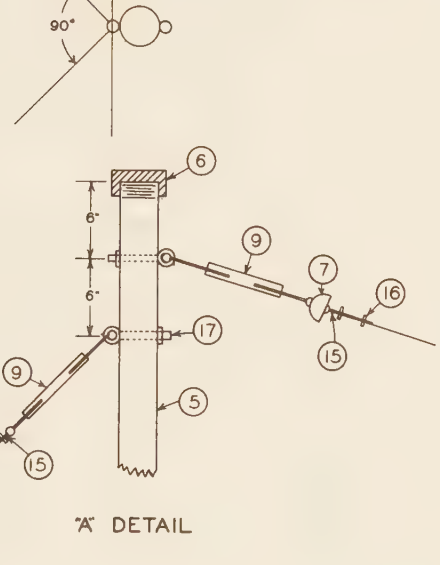

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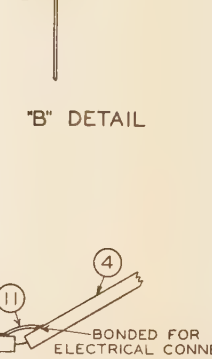

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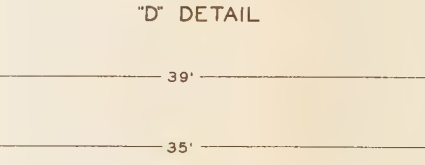

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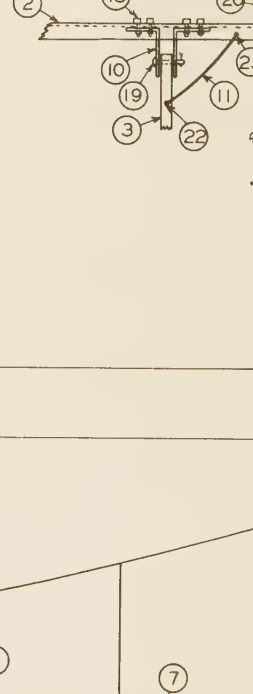

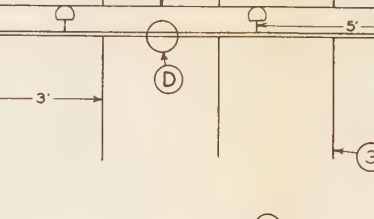

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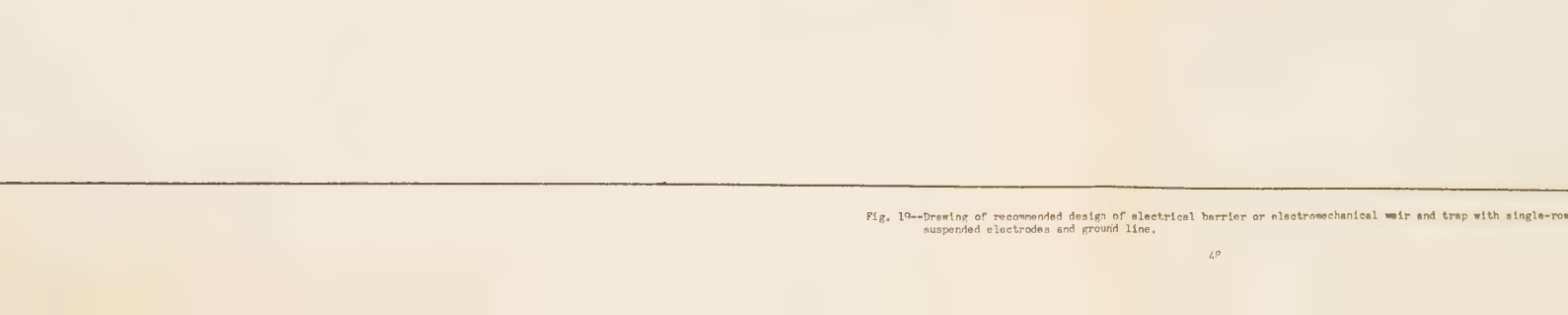

Fig. 19--Drawing of recommended design of electrical barrier or electromechanical weir and trap with single-row suspended electrodes and ground line.

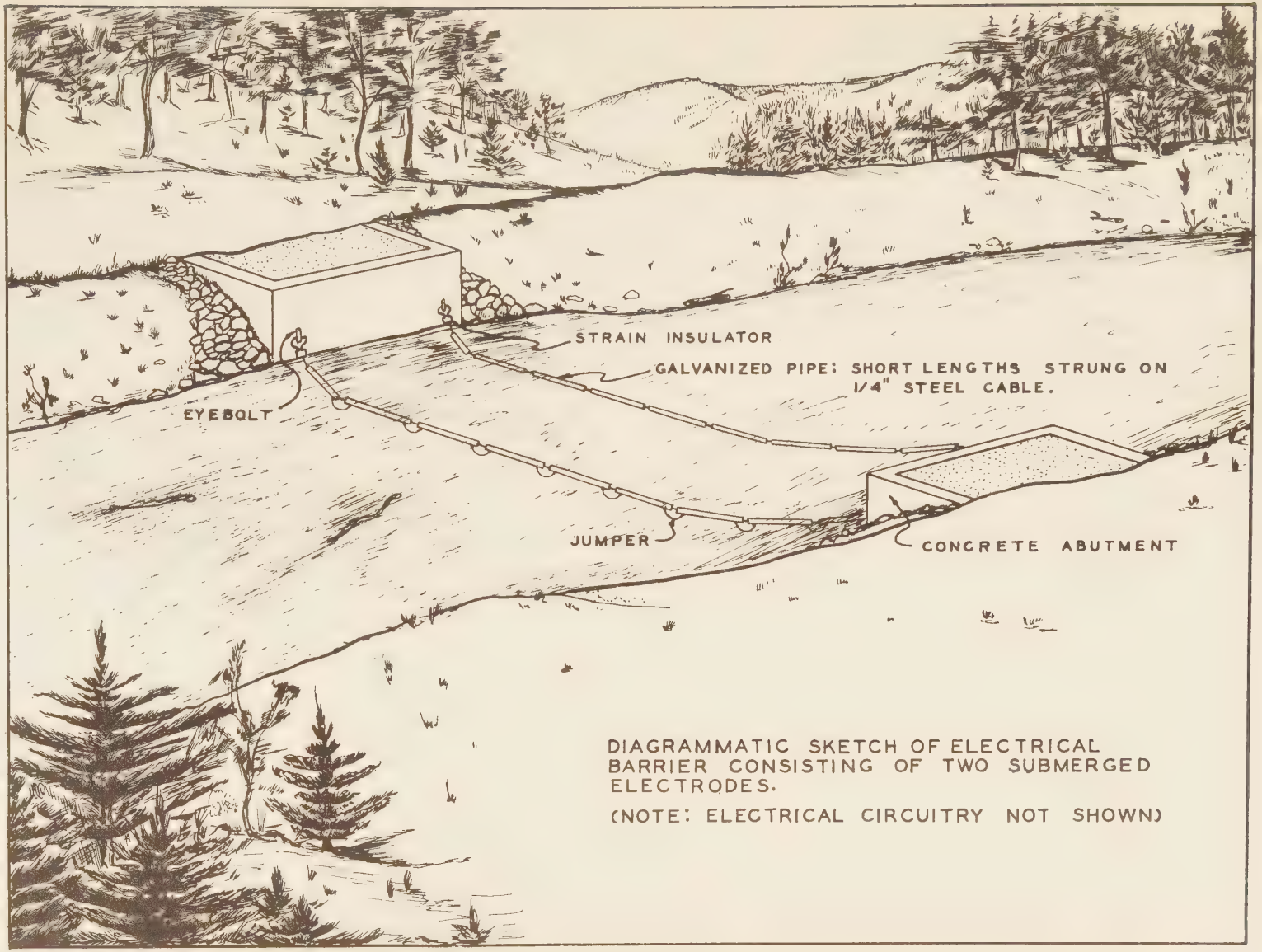
STRAIN INSULATOR
GALVANIZED PIPE: SHORT LENGTHS STRUNG ON 1/4" STEEL CABLE.
EYEBOLT
JUMPER
CONCRETE ABUTMENT
DIAGRAMMATIC SKETCH OF ELECTRICAL BARRIER CONSISTING OF TWO SUBMERGED ELECTRODES.
(NOTE: ELECTRICAL CIRCUITRY NOT SHOWN)

Fig. 20--Diagrammtic plan of recommended design of electrical barrier consisting solely of two lateral submerged electrodes.

extending further in an upstream or downstream direction) or by increasing the electrical efficiency of the shunt (connecting shunt screen to steel rods driven into the bed of the stream).

The use of domestic power lines as the sole source of power (System 1 as described in a previous section) in the operation of electromechanical weirs and traps and electrical barriers has proven to be entirely satisfactory. However, since the requisite 100-percent effectiveness of an electrical sea lamprey control device depends upon its uninterrupted operation during the entire sea lamprey spawning run, the use of an automatic starting generator as a standby source of power is recommended. In remote areas, inaccessible to commercial power of any sort, two complete power generating plants (System 3) must be used, each equipped with its own starting batteries and fuel supply. One of these generators must function as the "normal" source of power; while the other is held in readiness as the "standby" source. The normal source generator must deliver 115 volts, single phase, 60 cycle alternating current at power levels determined by the stream width and depth and a number of factors as discussed in Section (6) of the "Summary of Results in 1952". This generator must have such features as manual ("push button") starting, individual starting batteries with provision for automatic charging, and a completely independent fuel supply. It is recommended that the Kohler Company Series L21 generating plants or equivalent be used for this application. The standby generator also must deliver 115 volt, single phase, 60 cycle alternating current, and its power capability must be equal to that of the normal source generator. This generating plant must start automatically and transfer the load from the normal source to itself immediately upon failure, for any reason, of the normal source of power. Like the main generator, it must also be equipped with individual starting batteries with provision for automatic charging and an independent fuel supply. The Kohler Company Series E21 automatic standby plants or equivalent are recommended for use as emergency sources of power in conjunction with a domestic power line as the normal source in a System 2 supply, or with a generating plant as the normal source in a System 3 supply.

When the electrical weir site is to be located at a distance from the nearest power line, the choice between a System 2 and System 3 power supply will be governed by a number of factors. First, the construction and maintenance costs of a connecting power line in a System 2 installation must be weighed against the costs of a normal source generator which, in a System 3 supply would replace the power line. Where the electrical weir may be expected to require very high levels of power, and consequently a normal source generator of large capacity (over 10 KW), then a System 2 supply would probably be the most economical where the weir site is located up to 2 miles from the nearest power line. However, where the maximum anticipated power consumption of a weir is 2 KW or less, the installation of a power line over a half-mile long would in general not be economically advantageous and a System 3 supply accordingly would be desirable. Another factor to be considered is accessibility to the

weir site for the periodic delivery of the fuel required by a System 3 supply. Local electric power rates, although a consideration of less significance, might also affect the choice of power supply system for a particular weir.

It cannot be emphasized too strongly that all of the electrical devices described in this report are extremely dangerous if not approached and/or handled properly by experienced personnel. Ample opportunity exists for inquisitive persons, not familiar with the devices, to electrocute or at least seriously harm themselves. For this reason, all installations must be adequately fenced in a manner that will discourage curious individuals. So-called "cyclone" fencing surmounted by triple strands of barbed wire is recommended. Generator housings and access gates should be locked and prominent "warning-high voltage" signs posted on all facings of the enclosing fence. In addition, the circuitry of the installation should provide for the operation of several red "warning" lights which can be placed in prominent locations on the suspension towers.

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